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EXPERIMENTAL INVESTIGATION OF DEPOSITION BY BORON-CONTAINING FUELS IN TURBOJET COMBUSTOR (U)

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RESEARCH MEMORANDUM

EXPERIMENTAL INVESTIGATION OF DEPOSITION BY BORON-CONTAINING FUELS IN TURBOJET COMBUSTOR

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SUMMARY

An experimental investigation was conducted with trimethyl borate azeotrope and pentaborane fuels in a turbojet combustor. The effect of boron oxide deposits on the turbine-nozzle area, combustor pressure loss, temperature distribution, and combustion efficiency is included in the study.

An air-atomizing fuel nozzle produced a somewhat higher deposition rate (ratio of solids deposited to oxide formed) in the liner than the standard duplex fuel nozzle of the J47 engine did and provided a lower outlet-temperature spread.

Omitting the thimbles from the standard J47 engine liner, or enlarging nine holes in the "root" portion of the thimbled liner, made little change in the deposition rate but did modify the outlet-temperature distribution.

Deposition rate was relatively unaffected as combustor-outlet temperature was decreased from 1600° to 1200° F; below 1200° F the rate increased rapidly. The deposits decreased the effective turbine-stator area faster as the temperature was decreased. The burning of JP-4 fuel to remove boron oxide deposits from the combustor-liner walls at gas temperatures to 1725° F was ineffective. The ratio of the weight of deposits on the combustor liner to the total weight of boron oxide formed in the combustor was lower for pentaborane than for trimethyl borate azeotrope.

The influence of fuel additives on combustor deposits was investigated. Potassium hydroxide added directly to boron oxide reduces the viscosity of boron oxide and, therefore, would be expected to reduce the tendency of the boron oxide to stick to surfaces. However, when 0.5 and 1.5 percent potassium hydroxide was added to the trimethyl borate fuel the deposits in the combustor increased.

Condensed boron oxide deposits in the turbine-nozzle passages in three distinct ways:

(1) A fine film is deposited by the very small droplets formed in the flame zone. This film does not grow to any appreciable thickness.

(2) Large drops of boron oxide are carried off the film on the liner walls by the air streams entering the liner. When these drops impinge on a stator blade they adhere for several seconds.

(3) The film on the walls of the transition section between combustor and turbine stator flows into the stator annulus and passes along the inner and outer walls.

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INTRODUCTION

In order to determine combustion characteristics of such boron hydride fuels as diborane, pentaborane, and pentaborane-hydrocarbon blends in turbojet combustors, experimental investigations were initiated at the request of the Bureau of Aeronautics, Department of the Navy, as part of Project Zip. Results of this work have shown that it is necessary to reduce the deposits formed in combustors when burning boron hydride fuels (ref. 1). These deposits can distort outlet-temperature profiles, increase combustor pressure losses, and reduce turbine efficiency.

Combustor deposits of two different types have been noted, and these are believed to form by two different mechanisms: (1) boron hydrides decompose rapidly above 300° F (ref. 2) and yield solid products that are much less reactive than the original material; and (2) boron oxides formed during combustion can adhere to combustor surfaces and build up to objectionable size. Deposits formed principally by the first of these processes are described in references 1 and 3, where burning for a short time produced deposits around the fuel injector. These deposits interferred with the fuel spray. In both tests, it was found that modifying the air-flow pattern in the region of the fuel spray could eliminate this kind of deposit. In each case, the beneficial modifications involved bringing additional cool air around the fuel nozzle and promoting fuel-air mixing close to the fuel nozzle. These changes reduced the fuel temperature inside the nozzle and also reduced the time that fuel droplets are exposed to flame radiation before becoming mixed with sufficient air to burn. In the more recent investigations with boron hydride fuels, adequate cooling and fuel-air mixing are provided at the fuel injector; in these tests the deposits consist principally of a glassy boron oxide film on the walls of the conventional combustor liner (refs. 4 and 5).

The size of boron oxide particles formed at turbojet combustor conditions does not exceed 1.5×10^{-5} centimeters if these particles are not allowed to come in contact with the combustor walls (ref. 6). It was concluded that such small particles follow the flow streamlines and are

brought to the walls principally by motion of molecular collision and not by aerodynamic or inertia forces. Large particles of boron oxide have been observed in the gas stream coming from conventional combustors when burning boron-containing fuels. These large particles would not be expected to follow the flow streamlines. Consequently, they are deposited on the walls where there is a change in the shape of the flow passage; for example, in the turbine-inlet transition duct and in the turbine-nozzle diaphragm. As postulated in reference 6, these large particles of boron oxide are formed in the combustor in a definite manner: Some of the tiny boron oxide particles that are formed in the gas stream are deposited on the walls of the combustor liner. This results in a film of molten boron oxide that flows along the walls of the combustor liner. The gas stream in the combustor picks up portions of the oxide film to form the large particles.

An experimental turbojet combustor designed to eliminate deposits was investigated in reference 4. The combustor was fabricated of a porous wire cloth. A large quantity of air entered at the upstream end of the combustor liner to eliminate the recirculatory flow. Liner surfaces were filmed with air entering through the pores in the liner wall. The deposits in this combustor were greatly reduced; however, the combustor-outlet temperature profile was unsatisfactory and the combustor would not burn conventional jet fuel efficiently.

The ultimate solution to the problem of deposition when burning boron hydride fuels in turbojet combustors would appear to be in combustors especially designed for this purpose. While such a combustor is being developed, however, it is necessary to provide an interim combustor that can burn boron hydride fuels with sufficient freedom from deposits to permit short-duration engine tests of these fuels. A conventional turbojet combustor with minor modifications appeared adequate for these requirements. Furthermore, this combustor will burn conventional jet fuels which makes possible facility and instrumentation checks in advance of the special fuel test.

The object of this investigation was to study factors affecting the deposition of boron oxide in a conventional turbojet combustor so that methods of controlling deposition can be established. The investigation was conducted with a single J47 tubular combustor in a directly connected duct rig. The boron-containing fuels used in this investigation were pentaborane and trimethyl borate - methanol azeotrope. Test conditions simulated rated engine speed at 44,000 feet altitude and a flight Mach number of 0.6. The study included the effect on combustor deposits of (1) fuel-nozzle and liner-design modifications, (2) mean combustor-outlet temperature, (3) viscosity reduction of boron oxide by a fuel additive, and (4) intermittent burning with jet fuel. Data are also presented on combustion efficiency, pressure loss, and temperature profiles. Comparisons are made between these data and the results of a full-scale engine investigation of these same boron-containing fuels.

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APPARATUS

Combustor Installation

The combustion air was passed through a heat exchanger and then metered to the test installation (fig. 1); combustion products were discharged into an exhaust system.

The tests were conducted in a single combustor from a J47 engine. Three different combustor liners were used; a standard liner with thimbles (figs. 2 and 3), a standard liner without thimbles, and a standard liner with nine of the thimbled holes enlarged (fig. 3). They are designated hereinafter as A, B, and C, respectively.

The combustor-inlet and -outlet transition sections were segments of the corresponding sections of the complete engine. For part of the test work the turbine nozzle annular section was modified so that it "necked down" to the cross-section area of the nozzle passages. Simulated blades were installed in the "necked down" area (fig. 1). The surface area of the cluster of blades and the passage area between them duplicated the surface and throat areas of the nozzles behind each combustor in the engine.

Instrumentation

The arrangement of total-pressure probes and thermocouples is shown in figure 4. The total-pressure probes in the exhaust stream were provided with a source of air so that a continuous flow out of the openings could be maintained to keep them clear of deposits. The flow rate was held low so that it caused a negligible error in the total-pressure measurement. Temperature rakes 1, 3, 5, and 7, in section DD were each replaced with two total-pressure probes for the tests where the simulated turbine-nozzle section was used.

Fuel Systems

The fuel systems and the method of supplying air for atomizing the fuel are shown in figure 5. The JP-4 fuel system was used to bring the combustor into temperature equilibrium by burning the JP-4 fuel at test condition before the test fuel was turned on. The test-fuel system was provided with a JP-4 flush-fuel tank to purge the system immediately after pentaborane tests were made.

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The fuels used in this investigation are described in table I.

Fuel Nozzle

The fuel nozzles used in the investigations of pentaborane, pentaborane - JP-4 blend, and trimethyl borate fuels are shown in figure 6. The six-port air-atomizing nozzle (I) used for the trimethyl borate fuel tests in the single combustor test set up for this investigation is shown in figure 6(a). The spray was extremely fine and the spray cone was not hollow. The standard J47 duplex fuel nozzle (II) used for a trimethyl borate test is shown in figure 6(b). The six-port air-atomizing nozzle (III) used for the pentaborane tests in this investigation is shown in figure 6(c). This nozzle had three ports for injecting and atomizing JP-4 fuel so that both fuels could be burned simultaneously in varying proportions. In the investigations reported in references 4 and 5, a single-port air-atomizing nozzle (IV, fig. 6(d)) was used for pentaborane and pentaborane - JP-4 blends. This nozzle provided a much narrower cone angle than any of the others.

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PROCEDURE

Test Conditions

The single combustor investigation was made at the following conditions:

Combustor-inlet temperature, ^{o}F	368
Combustor-inlet total air pressure, in. Hg abs	34
Air flow, lb/sec	2.57
Simulated flight altitude, ft	44,000
Simulated flight Mach number	0.6
Simulated engine speed, percent of rated	100

Table II lists the test runs and data of the tests made in this investigation and also includes test data from references 4 and 5.

Except for the tests on the porous-wire-cloth combustor described in reference 4, JP-4 fuel was burned to warm the equipment to test conditions before the trimethyl borate or pentaborane fuels were turned on. The warming period served to reduce thermocouple radiation error and prevent rapid accumulation of deposits on cold combustor walls. When the simulated turbine-nozzle section was used in the single combustor tests the exhaust plenum pressure was reduced so that the flow was always choked at the nozzle.

Calculations

Combustion efficiency η_b was calculated from the relation

$$\eta_b = \frac{\text{enthalpy rise across the combustor}}{\text{heat of combustion of the fuel}}$$

The enthalpy of the stream entering and leaving the combustor was determined from temperature and pressure measurements and the thermodynamic properties of the reactants and combustion products determined from the data in reference 7. It was assumed there was no dissociation in the combustion products.

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Combustor-outlet temperature. - The average combustor-outlet temperature was calculated as the arithmetic mean of all the thermocouples in section DD (figs. 1 and 4).

Combustor pressure loss. - The total-pressure loss through the combustor was calculated as the dimensionless ratio of the measured total-pressure drop ΔP (total-pressure difference between stations AA and CC) to the dynamic pressure q. The dynamic pressure q was calculated from the combustor-inlet density, the air-flow rate, and the maximum cross-sectional area of the combustor housing of 0.48 square feet.

Temperature spread. - The temperature spread ΔT was the difference between the lowest and highest temperatures measured by the individually wired thermocouples of section DD (fig. 4).

Mean temperature deviation. - The mean temperature deviation was the arithmetic mean of the absolute values of the difference between each of the temperatures measured by the individually wired thermocouples and the mean temperature at section DD (fig. 4).

Radial-temperature profile. - The data for plotting the radial-temperature profile were found by averaging thermocouples at the same radial depth in rakes 2, 4, and 6 of section DD (fig. 4).

Circumferential-temperature profile. - The average of the five temperatures on each rake (2, 4, and 6) were used to plot the circumferential-temperature profile.

Deposition rate. - The deposition rate was taken as the weight ratio of the solids deposited on the combustor liner to the total boron oxide formed by complete combustion of the fuel.

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A_E Effective open area of turbine stator. - The effective area ratio of the stator-blade section was defined as

$$A_E = \frac{\text{effective open area of the blade section at any time}}{\text{effective open area of the blade section before deposition}}$$

Each of the areas were computed from the continuity relation

$$A = \frac{W_g}{p}\sqrt{\frac{Rt}{\gamma g}}$$

where

A area

W_g the sum of the rates of air and fuel flow minus the solid combustion products

p static pressure at the blade section

t static temperature at the blade section

g acceleration due to gravity

R,γ thermodynamic constants for the combustion gases

RESULTS AND DISCUSSION

Combustor Evaluation with Trimethyl Borate - Methanol Azeotrope Fuel

Because of the limited supply of pentaborane, most of the tests were conducted with trimethyl borate fuel.

Visual studies of deposits. - A window was installed in the single-combustor test apparatus (fig. 1) in order to observe how the open area of the simulated turbine-nozzle blades became constricted when trimethyl borate fuel was used. It could be seen that oxide reached the simulated blades in three distinct ways:

(1) A few seconds after the trimethyl borate was started the blade surface became wetted with a very fine film of oxide that did not increase in thickness. This is the wetting from the very small droplets formed in the flame zone which have not impinged on an upstream surface.

(2) Soon after, drops carried from the growing film on the liner surfaces appeared in the gas stream in increasing numbers. When these drops impinge on the leading edge of a blade they adhere at first, are slowly stretched out into a filament by the stream forces, and are removed within a few seconds.

(3) The film on the transition section between combustor and stator grows until it begins to flow downstream. Its progress to the annular walls of the blade section is slow and can be followed visually.

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Effect of operating time and fuel-nozzle design. - The total deposit weights and the deposition rates are shown in figure 7 for tests of trimethyl borate fuel in a standard liner with thimbles for a temperature range from 1425° to 1550° F. All tests, except run 19, were made with the six-port air-atomizing nozzle. An air-atomizing nozzle is not necessary for trimethyl borate fuel but it was desired to achieve a flat combustor-outlet-temperature profile so that the combustor could be used in a subsequent full-scale turbine performance investigation. In addition, it was desired to keep the trimethyl borate fuel injection similar to that for pentaborane in order to learn whether the deposits are similar for the two fuels.

A curve is faired through the data obtained with the air-atomizing nozzle. The total deposition and rate of deposition with the J47 duplex nozzle were lower than for the air-atomizing nozzle. The smaller cone angle of the spray of the J47 duplex nozzle is believed to have reduced the length of liner exposed to boron oxide deposits. Also, the air-atomizing nozzle provided faster fuel-air mixing, and therefore the flame zone occurred farther upstream. Combustion efficiency varied from 93 to 99 percent and was not measurably affected by the change of nozzles.

The temperature spread and the mean temperature deviation of the combustion gases at the turbine-nozzle inlet for the two fuel nozzles is shown in figure 8. Typical radial-temperature profiles of the two fuel nozzles is shown in figure 9. Each radial temperature is the mean of the three temperatures measured by rakes 2, 4, and 6 (fig. 4). The air-atomizing injector gave a lower temperature spread and lower temperature deviation than the standard J47 fuel nozzle but the radial-temperature profiles for the two nozzles were about the same.

Temperature distribution in a test of longer duration with an air-atomizing nozzle provided faster fuel-air mixing, and therefore, the flame zone occurred farther upstream. Combustion efficiency varied from 93 to 99 percent and was not measurably affected by the change of nozzles. ture spread and mean temperature deviation continue to increase throughout the run, whereas the radial-temperature profile (fig. 11) changes very little with time. The radial-temperature profile with JP-4 fuel is included to show its similarity to the trimethyl borate profile. The

growing maldistribution of temperature is principally circumferential (fig. 12) and it is apparent that an engine could not operate very long as this temperature spread increases.

The combustor-pressure loss was about the same for each of the nozzles and stayed approximately constant at a value of 10 for the duration of each of the tests with trimethyl borate fuel (table II). Unpublished tests on a full-scale J47 engine using trimethyl borate fuel and in the same combustor-outlet-temperature range showed no variation of combustor pressure loss with time.

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Effect of combustor-liner modifications. - It appeared that the thimbles could be providing shelters which promoted the collection of oxides (fig. 13(a)). In order to determine the influence of thimbles on deposition, tests were made on a liner without thimbles (fig. 13(b)). In order to improve the outlet-temperature profile, tests were also conducted on a liner with nine enlarged holes (fig. 13(c)). The three liners are shown after each one had run about 70 minutes with trimethyl borate at about 1550° F. The weight of deposits in the liner with enlarged holes (C) was not recorded with the test results because the fuel flow was unintentionally interrupted several times during the test.

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The deposition rate for the liner without thimbles (B) and the deposition rate for the liner with thimbles (A)(fig. 7) is shown in figure 14. From these data and the photographs in figure 13, these liner variations apparently have no important effect on deposition rate.

In the course of the full-scale J47 tests with trimethyl borate fuel, a six-port air-atomizing fuel nozzle, and a standard liner with thimbles, a turbine-wheel failure occurred that could have been due to high temperature at the blade root. The liner with nine enlarged holes was used to lower the temperatures near the turbine blade root. This modification lowered the root temperature about 200° (fig. 15). Omitting the thimbles or enlarging the holes increased the temperature spread and the mean temperature deviation (fig. 16). Neither of the modifications had any measurable effect on the combustion efficiency.

Effect of combustor-outlet temperature. - The effect of combustor gas temperature on deposition for single combustor and full-scale engine investigations are shown in figure 17. (The full-scale engine test conditions were a flight altitude of 55,000 feet, flight Mach number of 0.8, and 100-percent rated engine speed.) The deposition-rate curve (fig. 7) for trimethyl borate fuel over a temperature range of 1425° to 1550° F is reproduced for comparison. The deposition-rate data for combustion temperatures from 1000° to 1615° F show that there is no appreciable increase in deposition until the temperature drops below 1277° F. At 1000° F the rate is about twice that at 1277° F.

The decrease in effective turbine-nozzle area by boron oxide deposits is shown in figure 18. The decrease is much more rapid at 1320° F than at 1550° F. Effective turbine-nozzle-area calculations for the full-scale engine tests showed trends similar to these single-combustor tests; however, the nozzle-area reduction was less in the full-scale engine tests. The decrease in area with time in the turbine stator of a J47 engine fueled with trimethyl borate is shown in figure 19 for combustor-outlet temperatures of 1277° and 1615° F. At the higher temperature there was no measurable decrease in turbine-nozzle area; at the lower temperature there was about a 3-percent decrease in turbine-nozzle area in 2 hours.

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The effect of mean combustor-outlet temperature on radial-temperature profile for JP-4 and trimethyl borate fuels in the liner with thimbles (A) is given in figure 20. The profiles with JP-4 fuel were determined to see what the combustor behavior is with a nondepositing fuel. The JP-4 profile curvature increased with temperature. The trimethyl borate profiles were similar to those obtained with JP-4 fuel except that at the highest temperature, 1725° F, the temperature became much higher at the root than at the tip. The probable cause for the profile distortion became apparent when the nozzle was operated with water in order to observe the spray properties. The liquid flow rate of the trimethyl borate at 1725° F was found to be above the capacity of the nozzle to produce a fine spray.

Effect of potassium hydroxide as a fuel additive. - Potassium hydroxide was used as a fuel additive because it has been shown to reduce the viscosity of boron oxide (refs. 8 and 9). Trimethyl borate fuel with 0.5 and 1.5 percent potassium hydroxide gave unexpectedly high deposition rates (fig. 21). The liner, transition section, and simulated turbine-nozzle section are illustrated in figure 22 when clean, after 5 hours of trimethyl borate fuel burning at 1550° F, and after 70 minutes of burning trimethyl borate fuel plus 1.5 percent potassium hydroxide at the same temperature; each fuel test beginning with clean apparatus. The pictures of liner and transition section clearly show the increased bulk of deposit when potassium hydroxide is added to trimethyl borate. The data given in figure 23 show that the decrease in stator area was accelerated when potassium hydroxide was added to the fuel. The pressure loss, temperature spread, and mean temperature deviation all increased much more with the 1.5 percent potassium hydroxide additive present (fig. 24). The radial-temperature profile fluctuated erratically with the fuel additive (fig. 25).

When the test was begun with the fuel additive the profile was similar to that obtained with the pure fuel (figs. 25 and 11). The change in temperature distribution was apparently due to disturbances in the flow pattern caused by deposits and was not a result of a change in the combustion property of the fuel. Analysis of the deposited material showed that the potassium hydroxide concentration was much higher than would result from a homogeneous mixture of the combustion products. The deposits

were soft and crumbly instead of hard and glossy as when trimethyl borate without an additive is burned. It appears then that potassium hydroxide deposits separately. The reduction in the viscosity of boron oxide indicated by the data of references 8 and 9 was possibly not realized because the potassium hydroxide did not have time to go into solution with the boron oxide before the condensed materials impinged on the liner walls.

Combustor Cleanout by Burning JP-4 Fuel

A test was made to determine whether the deposits in the liner and on other surfaces could be removed or reduced by changing to JP-4 fuel after a quantity of boron oxide had been deposited. Trimethyl borate and JP-4 fuels were burned in a standard combustor in the order and for the time periods and temperatures shown in figure 26. The temperature spread, mean temperature deviation, and pressure drop increased as trimethyl borate was burned in an initially clean, preheated combustor at 1500° F outlet temperature. Then JP-4 fuel was substituted for the trimethyl borate fuel without interrupting the burning or changing the temperature. One hour after the JP-4 fuel was started there was no appreciable change in temperature distribution or pressure drop. Trimethyl borate and JP-4 fuels were then successively burned at somewhat higher temperatures with no further change in temperature distribution or pressure drop. The appearance of the oxide deposits at temporary shutdown after 200 minutes of running and again at the final shutdown at 320 minutes is shown in figure 27.

Combustor Evaluation with Pentaborane Fuel

Deposition rate. - The curve of the deposition rate of pentaborane is compared with the curve for trimethyl borate deposition (fig. 7) in figure 28. All the data in figure 28 were taken at the same nominal combustor conditions. Runs 23 and 24 were made with the liner with nine enlarged holes (C) and the six-ported air-atomizing nozzle (III). The test from reference 5 was made with a 66.8-percent blend of pentaborane in JP-4 fuel in a J47 liner with thimbles (A) and with the single-port nozzle (IV). The data from reference 4 were taken under the same conditions as reference 5 except that pure pentaborane fuel and a porous-wire-cloth liner (liner D) were used.

The data of figure 28 show that the deposition rate with pentaborane is lower than with trimethyl borate for the configuration and conditions covered. A possible explanation for this phenomenon is suggested as follows:

Since a higher boron oxide concentration results from burning pentaborane fuel as compared with burning trimethyl borate fuel at the same

combustor temperature, the mean drop size of the condensed oxide will be larger. In the size range of 1×10^{-5} centimeters, motion of the particles to the duct walls results principally from molecular collisions. The frequency of collision will vary directly as the particles' projected area or the particles' diameter squared, and the velocity due to collision will vary inversely as the mass or the diameter cubed. The net effect is, as stated in Fick's law (ref. 10), that deposition, as herein defined, is inversely proportional to the particle diameter.

Comparison of the pentaborane data in the various combustor configurations shows that deposition is decreased by decreasing the cone angle of the fuel atomizer. Air filming the liner surfaces by the use of porous wire cloth further reduced the deposition.

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Combustion efficiency. - The combustion efficiency, determined from the enthalpy rise across the combustor was about the same for trimethyl borate and pentaborane fuels (fig. 29). Also, the efficiency did not change appreciably with time. In the pentaborane test of run 24, efficiency appears to increase from 96 to about 98 percent in the 20-minute-test period; however, it is believed that this is not a significant trend but only data scatter.

Temperature distribution. - The mean deviation and temperature spread obtained with pentaborane in the liner with nine enlarged holes (C) is shown in figure 30. The data scattered too much and the test period was too short to establish a trend. According to the trimethyl borate data, it is expected that with long-period operation the temperature spread and deviation will increase.

The radial-temperature profiles of several pentaborane tests, a trimethyl borate test, and a JP-4 test are shown in figure 31. The trimethyl borate profile curve from figure 11 (run 11), taken 5 minutes after the start of the test, is reproduced for comparison; this test was made at 1550° F with a thimbled liner (A) and the six-port air-atomizing nozzle (I). The profile from run 1 was taken when pure pentaborane was being burned in the same liner as run 11; however, the six-port air-atomizing nozzle (III) was used. With pentaborane the temperature was about 200° F higher at the root than at the tip; with trimethyl borate, the root and tip temperatures were nearly the same. Run 24 was made with pentaborane in the liner that had nine holes enlarged (C) to lower the root temperature. This modification was much less effective in lowering the root temperature with pentaborane than with JP-4 fuel (run 24, fig. 31) or trimethyl borate fuel (run 20, fig. 15).

The difference in the susceptibility of the two temperature profiles to liner modification is probably due in part to the difference in the fuel nozzles. The fuel injector is located on the liner centerline

which projects through the lower or root portion of the turbine annulus (fig. 1). Pentaborane burns close to the injector with much less fuel spreading than less reactive fuels like JP-4 and trimethyl borate. The shift from high to low root temperature with change in fuel is probably due to the change in flow pattern caused by the location and size of the flame zone. The temperature-profile curve from the data of reference 5 shows that a flatter radial-temperature profile results when the single-port fuel nozzle (IV) is used in a J47 thimbled combustor than when the same nozzle is used in a porous-wire-cloth liner (ref. 4).

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SUMMARY OF RESULTS

The following results were obtained from experimental investigation of deposition of boron-containing fuels:

1. Oxide deposits are formed on turbine-nozzle blades by (a) the small drops of oxide formed in the flame zone that wet the blade surfaces with a very thin film; (b) the large drops of oxide that are carried from the film on the liner walls by the air stream and impinge on the blade surfaces; and (c) the film on the transition section between combustor and stator that grows until it flows onto the annular walls of the turbine-nozzle blades.

2. An air-atomizing nozzle provided a lower outlet-temperature spread with trimethyl borate fuel, but a somewhat higher liner deposition rate, than the standard J47 duplex nozzle.

3. The oxide deposits on the liner and stator surfaces accumulated at a decreasing rate during 5 hours of burning trimethyl borate fuel in a standard J47 liner with thimbles.

4. Omitting the thimbles from a standard J47 liner, or enlarging nine holes in the root portion of the thimbled liner, made little change in the deposition rate for trimethyl borate fuel, but did modify the temperature distribution.

5. Deposition rate changed very little as combustor-outlet temperature was decreased from 1600° to about 1200° F. Below 1200° F the rate increased rapidly. The deposits decreased the effective turbine-nozzle area faster as the temperature was decreased.

6. The influence of fuel additives was investigated by adding 0.5 and 1.5 percent potassium hydroxide to trimethyl borate fuel. The potassium hydroxide added directly to boron oxide reduced the viscosity of boron oxide and, therefore, would be expected to reduce the tendency of the oxide to stick to surfaces. However, the use of this additive in the fuel increased combustor deposits.

7. The burning of JP-4 fuel to remove boron oxide deposits from combustor liner walls at temperatures up to 1725° F was ineffective.

8. The ratio of the weight of deposits on the liner to the total weight of boron oxide formed in the combustor was lower for pentaborane than for trimethyl borate azeotrope.

9. The combustion efficiency was about the same for trimethyl borate and pentaborane fuels.

10. Pentaborane gave a temperature profile with a higher root temperature than JP-4 or trimethyl borate fuels.

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Lewis Flight Propulsion Laboratory
National Advisory Committee for Aeronautics
Cleveland, Ohio, December 9, 1955

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TABLE I. - FUEL PROPERTIES

	Fuels		
	JP-4	Pentaborane	Trimethyl borate - methanol azeotrope
Lower heat of combustion, Btu/lb	[a]18,600	29,127	8052
Hydrogen-carbon ratio	[a]0.174	----	----
Pounds of boron oxide per pound of fuel	----	2.76	0.23

[a]Average of the batches used in this investigation.

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TABLE II. - DEPOSITION TEST DATA

Run	Run duration, min	Combustor liner	Fuel nozzle	Fuel	Time, data recorded, min	Combustor-inlet temperature, °F	Combustor-inlet total pressure, in. Hg abs	Air flow, lb/(sec)(sq ft)(a)	Fuel flow, lb/sec	Average combustor-outlet temperature, °F	Nozzle-inlet total pressure, in. Hg abs	Combustor-inlet velocity, ft/sec	Atomizing air flow, lb/sec	Combustion efficiency, percent	Pressure losses across combustor	Deposit weight at end of run, g
1	9.0	A	I	[b]40	1.5	367	33.0	5.32	0.040	1544	----	100	0.009	93	----	239
				[b]100	3.5	367	32.8	5.29	.028	1515	----	100	↓	99	----	
				[b]100	4.5	367	32.7	5.17	.028	1501	----	98		97	----	
				[b]40	6.5	368	33.0	5.29	.039	1534	----	100		92	----	
				[b]58	8.5	370	----	5.32	.036	1549	----	---	↓	93	----	
3	30.5	A	I	Trimethyl borate	5	372	32.6	5.49	0.116	1500	----	106	0.048	93	10.3	254
					15	376	32.7	5.45	.122	1596	----	105	↓	99	10.4	
					30	375	32.7	5.45	.122	1601	----	105		96	10.4	
4	70.5	A	I	Trimethyl borate	5	370	32.5	5.49	0.119	1555	----	106	0.048	96	10.7	452
					35	375	32.5	5.43	.115	1556	----	105	↓	98	10.5	
					70	376	32.6	5.49	.114	1546	----	106		99	10.3	
6	71.5	A	I	Trimethyl borate	5	347	35.5	5.69	0.113	1456	33.7	97	0.054	97	10.4	494
					35	360	36.2	5.53	.116	1516	34.3	94	↓	96	10.1	
					71	370	36.3	5.53	.115	1519	34.3	95		97	10.4	
7	60.5	A	I	Trimethyl borate	2.5	368	32.5	5.43	0.091	1320	30.5	104	0.051	97	9.8	447
					35	375	33.1	5.41	.091	1322	31.1	103	↓	98	9.8	
					60	367	34.6	5.59	.095	1336	32.6	101		96	9.8	
8	120	A	I	Trimethyl borate	----	---	----	----	0.0644	[c]1000	----	---	-----	--	----	795
9	33.5	A	I	JP-4	----	347	27.1	5.46	0.015	786	24.9	122	0.054	--	10.7	---
					----	363	31.3	5.51	.034	1215	29.4	109	↓	--	9.6	
					----	367	34.4	5.43	.052	1598	32.6	98		--	9.6	
				Trimethyl borate	3.5	367	36.5	5.43	0.140	1725	34.7	93	0.054	--	10.2	268
					8.5	363	34.9	5.44	.119	1556	33.0	96	↓	--	10.3	
					13.5	364	33.5	5.39	.103	1431	31.7	99		--	10.3	
					18.5	367	32.4	5.45	.088	1309	30.5	105		--	10.1	
					23.5	370	30.7	5.36	.068	1150	28.7	109		--	10.2	
					28.5	361	29.5	5.34	.052	994	27.7	112		--	10.0	
					33.5	372	30.3	5.46	.037	842	28.6	113	↓	--	10.6	
10	34.5	A	I	JP-4	----	359	27.1	5.41	0.014	811	25.0	123	0.055	--	11.0	---
					----	373	31.2	5.42	.034	1235	29.3	109	↓	--	10.5	
					----	370	34.6	5.43	.051	1620	32.8	98		--	11.1	
				Trimethyl borate + 1.5% potassium hydroxide	3.5	373	34.2	5.40	0.118	1550	32.4	99	0.055	--	9.3	823
					14.5	372	33.3	5.37	.099	1425	31.3	101		--	10.9	
					19.5	376	33.1	5.49	.086	1305	30.9	104		--	10.9	
					24.5	377	32.2	5.51	.064	1107	30.1	108		--	11.0	
					29.5	373	32.8	5.43	.050	981	30.9	104		--	----	
					34.5	375	36.3	5.47	.035	840	34.8	95	↓	--	----	

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11	300	A	I	Trimethyl borate	5	365	35.0	5.48	0.124	1560	33.2	97	0.053	93	9.5	1161
					60	370	35.7	5.57	.123	1558	33.8	97	↓	95	9.4	
					120	383	32.0	4.98	.107	1521	30.2	99		93	9.9	
					180	415	32.0	5.00	.106	1535	30.2	102		93	9.8	
					240	418	33.4	5.20	.108	1513	31.5	103		93	9.8	
					300	407	33.5	5.30	.104	1465	31.6	103		94	10.2	
12	70.5	A	I	Trimethyl borate + 1.5% potassium hydroxide	1	370	34.3	5.42	0.115	1528	32.5	99	0.054	97	9.7	2434
					30	373	36.0	5.45	.122	1594	33.6	95	↓	98	13.5	
					70	370	37.0	5.51	.123	1560	33.6	93		96	21.8	
13	71.5	A	I	Trimethyl borate + 0.5% potassium hydroxide	1	362	35.2	5.77	0.119	1514	34.3	101	0.054	98	9.7	1817
					30	366	34.7	5.48	.114	1528	32.7	98	↓	99	10.1	
					61	365	35.0	5.51	.112	1500	32.9	98		98	10.7	
18	70.5	B	I	Trimethyl borate	5	365	32.5	5.42	0.116	1511	30.5	103	0.054	93	12.5	378
					30	374	32.6	5.49	.116	1532	30.5	105	↓	96	12.2	
					70	373	32.7	5.48	.116	1534	30.5	105		96	12.2	
19	70.5	A	II	Trimethyl borate	10	362	33.0	5.38	0.118	1551	30.8	101	-----	96	10.8	321
					30	365	33.0	5.44	.115	1515	30.8	102		95	11.0	
					70	360	33.2	5.43	.114	1504	31.0	101		95	10.8	
[d]20	----	C	I	Trimethyl borate	-----	---	----	----	-----	----	----	---	0.009	--	----	---
23	6.2	C	III	Pentaborane	1	390	32.9	5.21	0.032	1606	31.2	101	0.014	93	12.1	110
					3	389	33.0	5.23	.033	1586	31.3	101	.009	89	12.4	
					4.5	386	33.0	5.26	.033	1495	31.3	101	.009	84	12.0	
24	23	C	III	JP-4	0	374	32.0	5.36	0.044	1487	30.1	105	0.015	95	11.6	---
				Pentaborane	3	363	32.0	5.44	0.030	1512	30.1	105	0.015	96	12.5	265
					9	366	32.1	5.41	.030	1515	30.1	105		96	12.3	
					15	359	32.2	5.45	.036	1534	30.2	104	↓	98	12.5	
					21	378	32.1	5.35	.035	1544	30.2	105		99	12.2	
27	-----	A	I	Trimethyl borate	1	359	32.2	5.56	0.107	1439	30.2	106	0.053	97	9.1	---
					120	367	32.6	5.52	.118	1504	30.3	105	.053	94	9.0	
				JP-4	201	367	32.4	5.54	0.048	1516	30.2	106	0.053	94	9.1	---
				Trimethyl borate	251	358	32.4	5.59	0.116	1473	30.2	106	0.057	95	9.2	---
				JP-4	292	366	32.4	5.47	0.052	1645	30.2	105	0.057	97	8.9	---
					312	347	32.6	5.64	.058	1724	30.3	105	.057	95	9.2	
Ref. 4	4.4	[e]D	[f]IV	Pentaborane	1	357	32.1	5.27	0.033	1557	----	101	0.004	89	----	36
					1.9	353	32.1	5.30	.033	1544	----	101		88	----	
					2.9	353	32.2	5.38	.033	1552	----	103	↓	90	----	
					3.9	354	32.2	5.39	.033	1557	----	103		91	----	
Ref. 5	4	A	IV	[b]66.8	1	368	32.6	5.44	0.037	1628	----	104	0.0074	97	13.9	71
					2	367	32.5	5.31	.038	1658	----	102	↓	96	14.0	
					3	367	32.4	5.27	.038	1676	----	101		96	13.9	

[a]Based on combustor area of 0.48 sq ft.
[b]Percent pentaborane in pentaborane - JP-4 blend.
[c]Nominal temperature measured at station D'D'.
[d]Run interrupted unintentionally several times.
[e]Porous-wire-cloth liner (ref. 4).
[f]Same as nozzle IV except that JP-4 fuel passages and orifices are omitted.

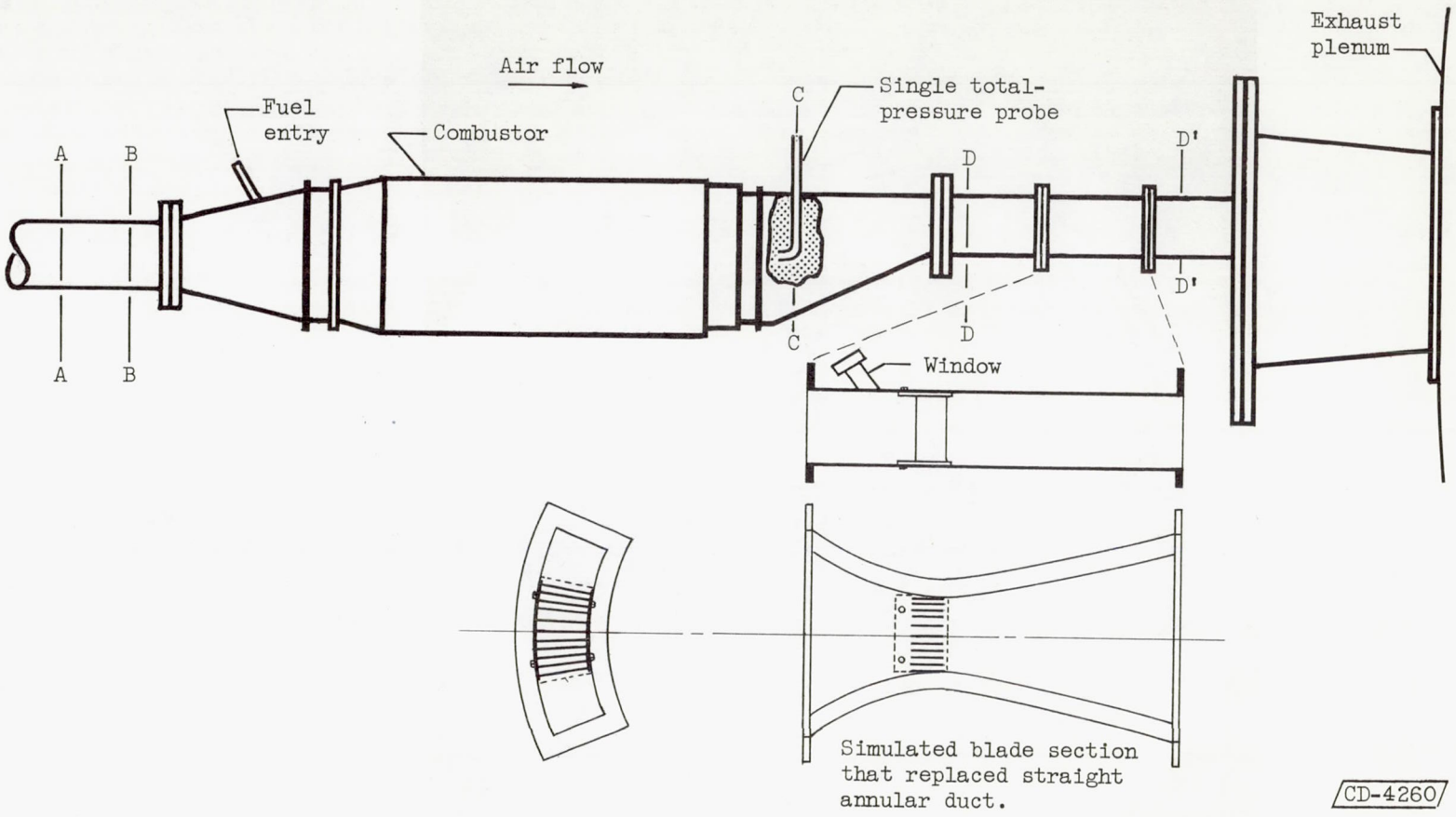


Figure 1. - J47 single combustor test installation.

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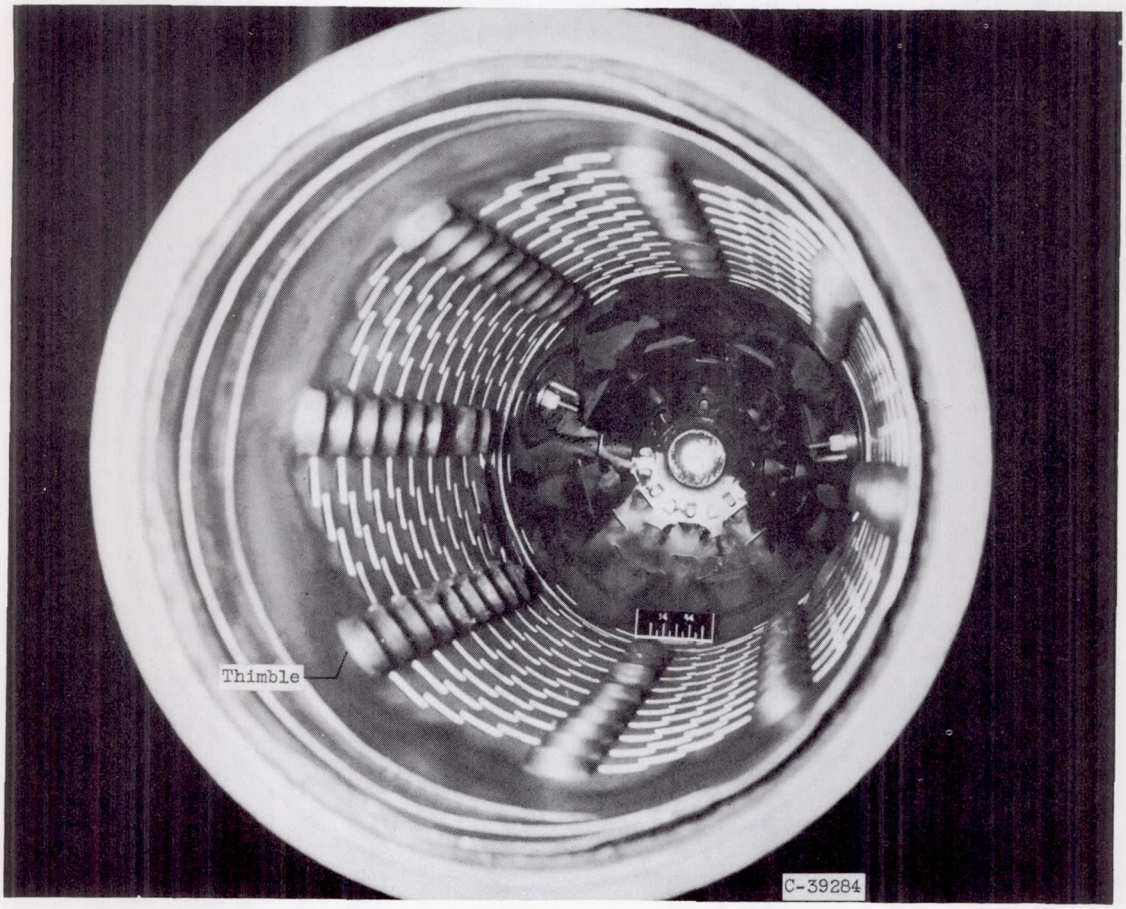
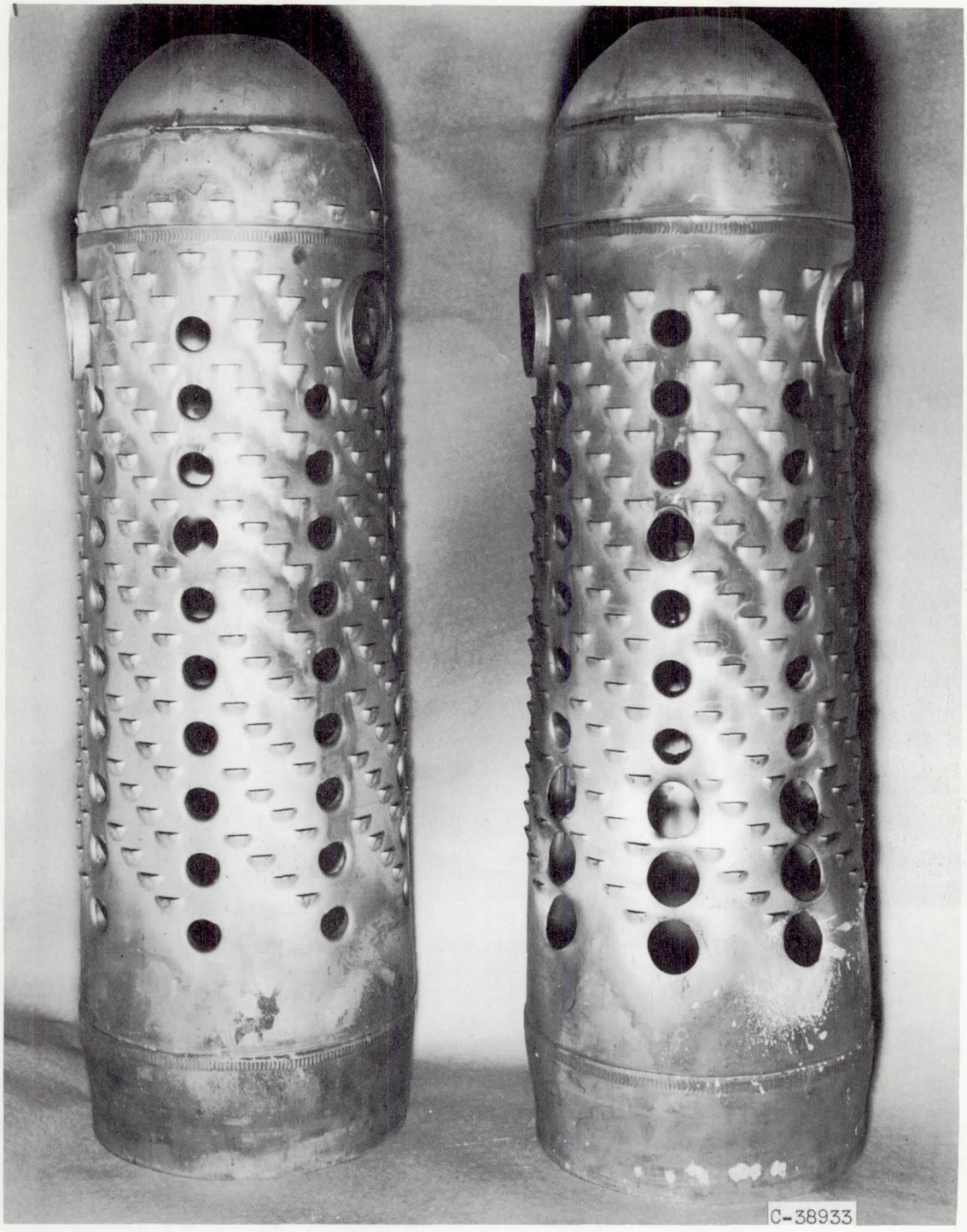


Figure 2. - Standard J 47 liner with thimbles. (Liner A)

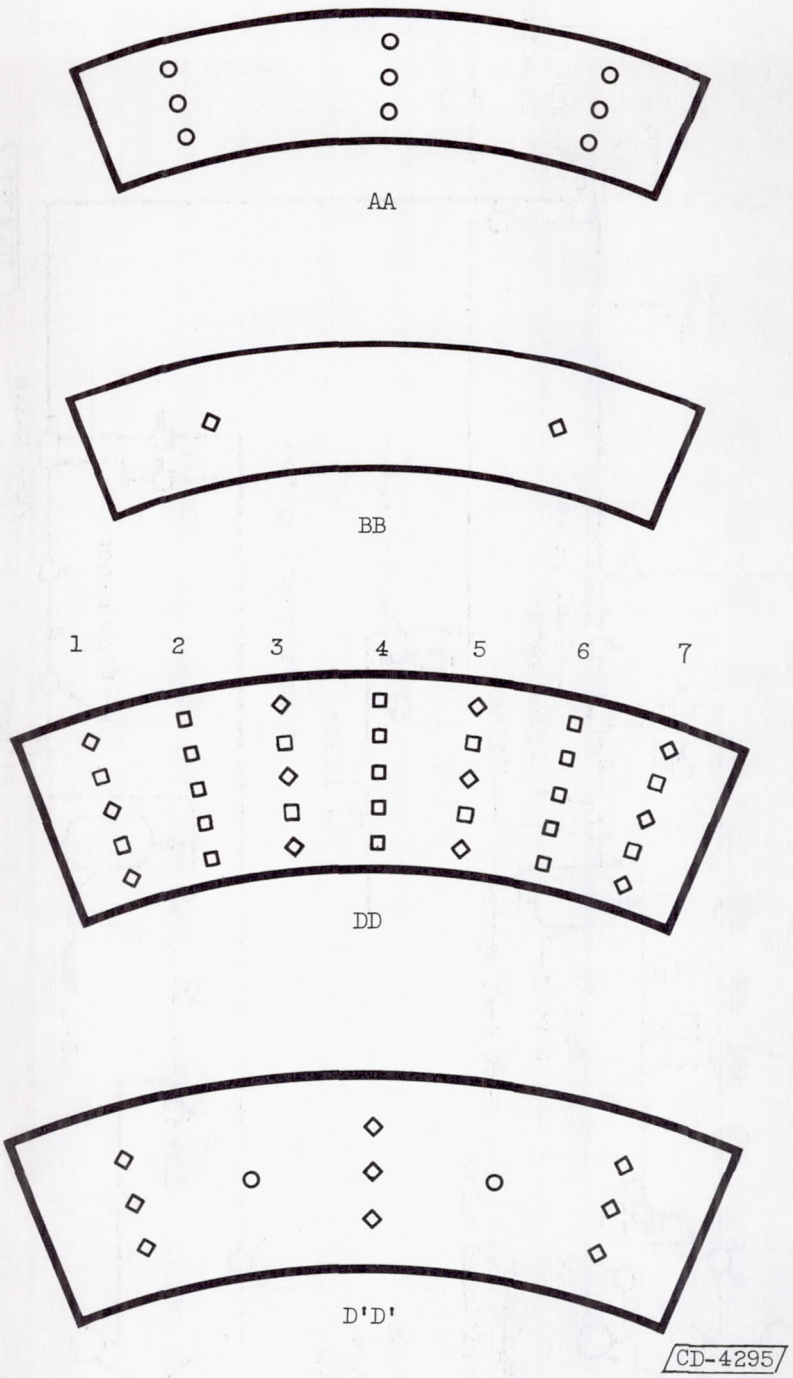
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Liner A Liner C

Figure 3. - Standard J47 liner with thimbles (A) and with nine enlarged holes (C).

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○ Total-pressure tubes

□ Thermocouples (wired individually)

◇ Thermocouples (wired in parallel)

Figure 4. - Instrumentation sections.

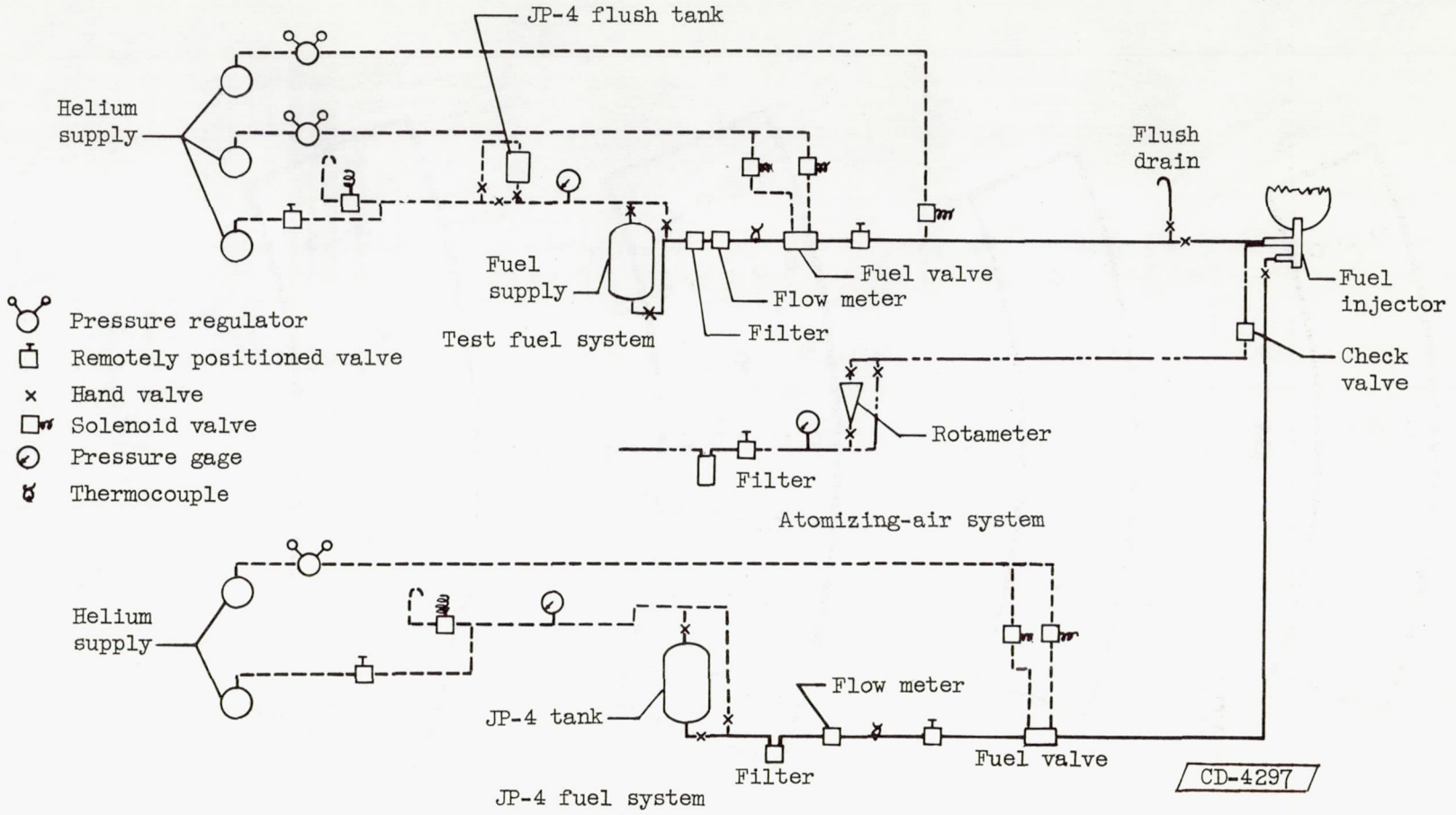
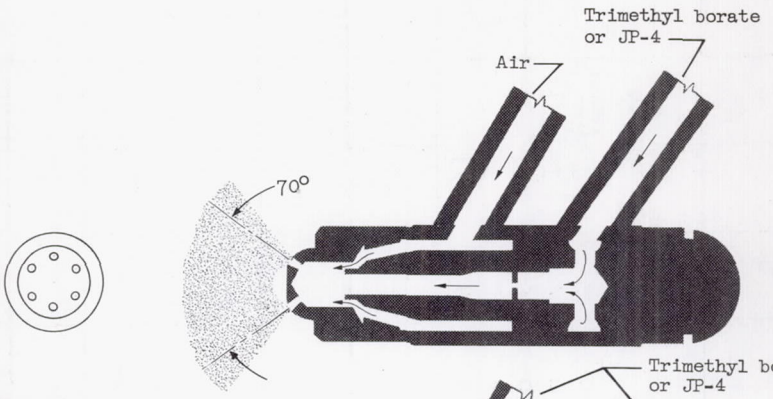
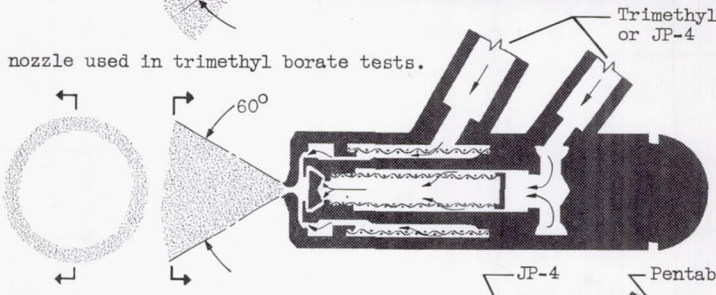


Figure 5. - Fuel and atomizing-air systems.

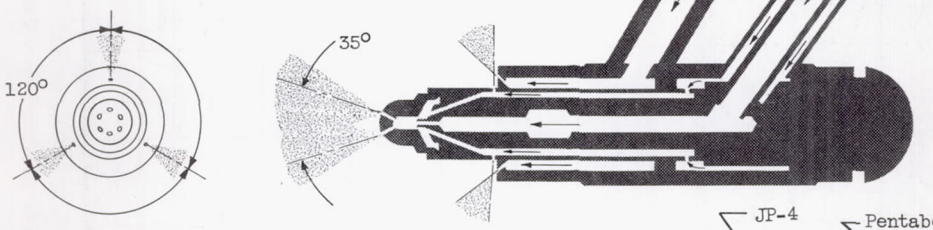
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CQ-4



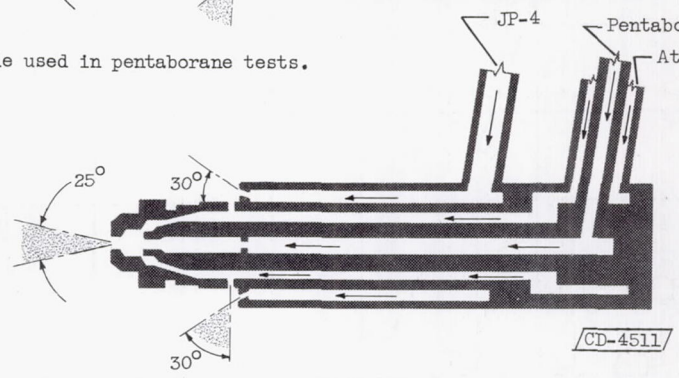
(a) Air-atomizing 6-port nozzle used in trimethyl borate tests. (Nozzle I)



(b) Standard J47 duplex nozzle. (Nozzle II)



(c) Air-atomizing 6-port nozzle used in pentaborane tests. (Nozzle III)



(d) Single-port air-atomizing nozzle. (Nozzle IV)

Figure 6. - Fuel nozzles.

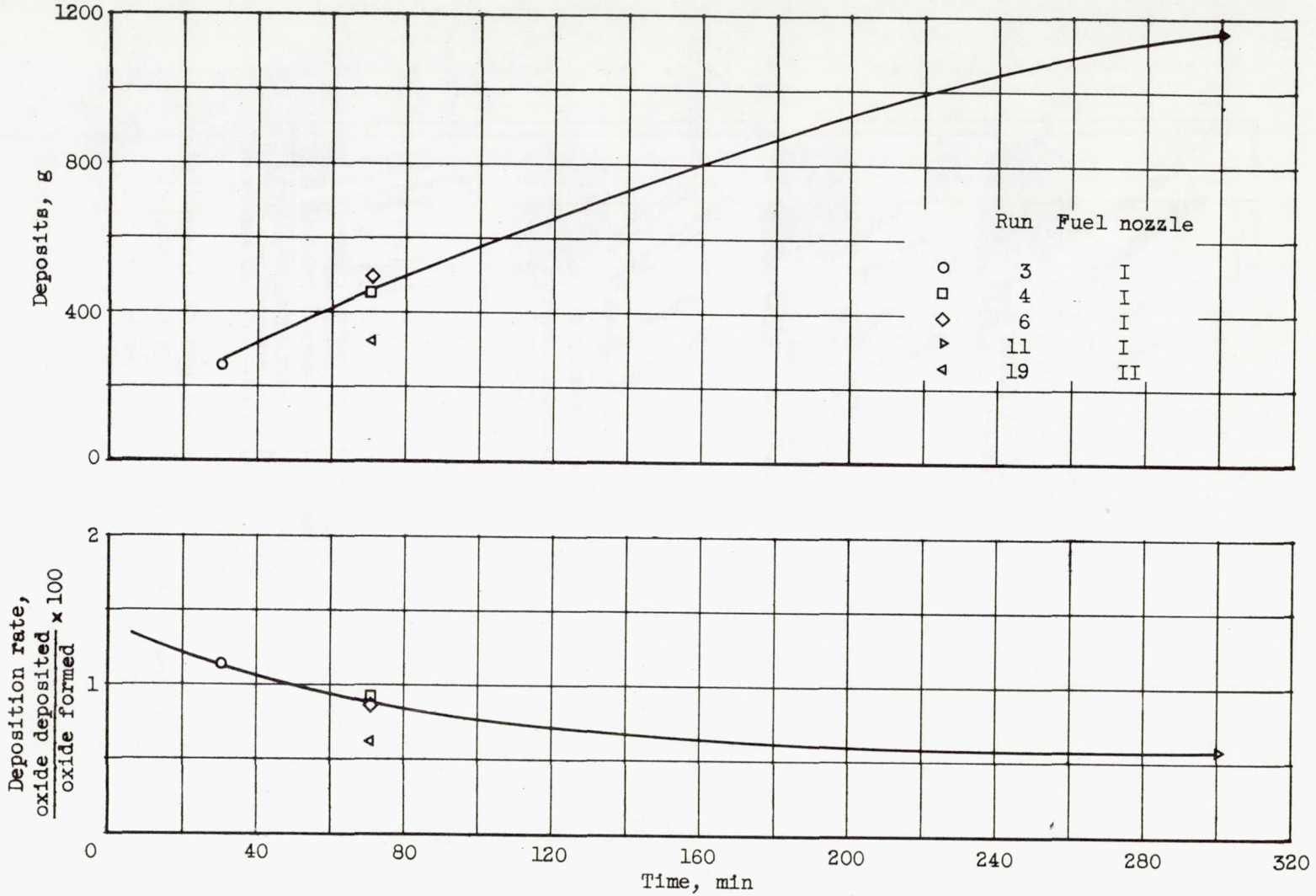


Figure 7. - Total liner deposits and deposition rate. Liner A; fuel, trimethyl borate; combustor-outlet temperature, 1425° to 1550° F.

3913 CQ-4 back

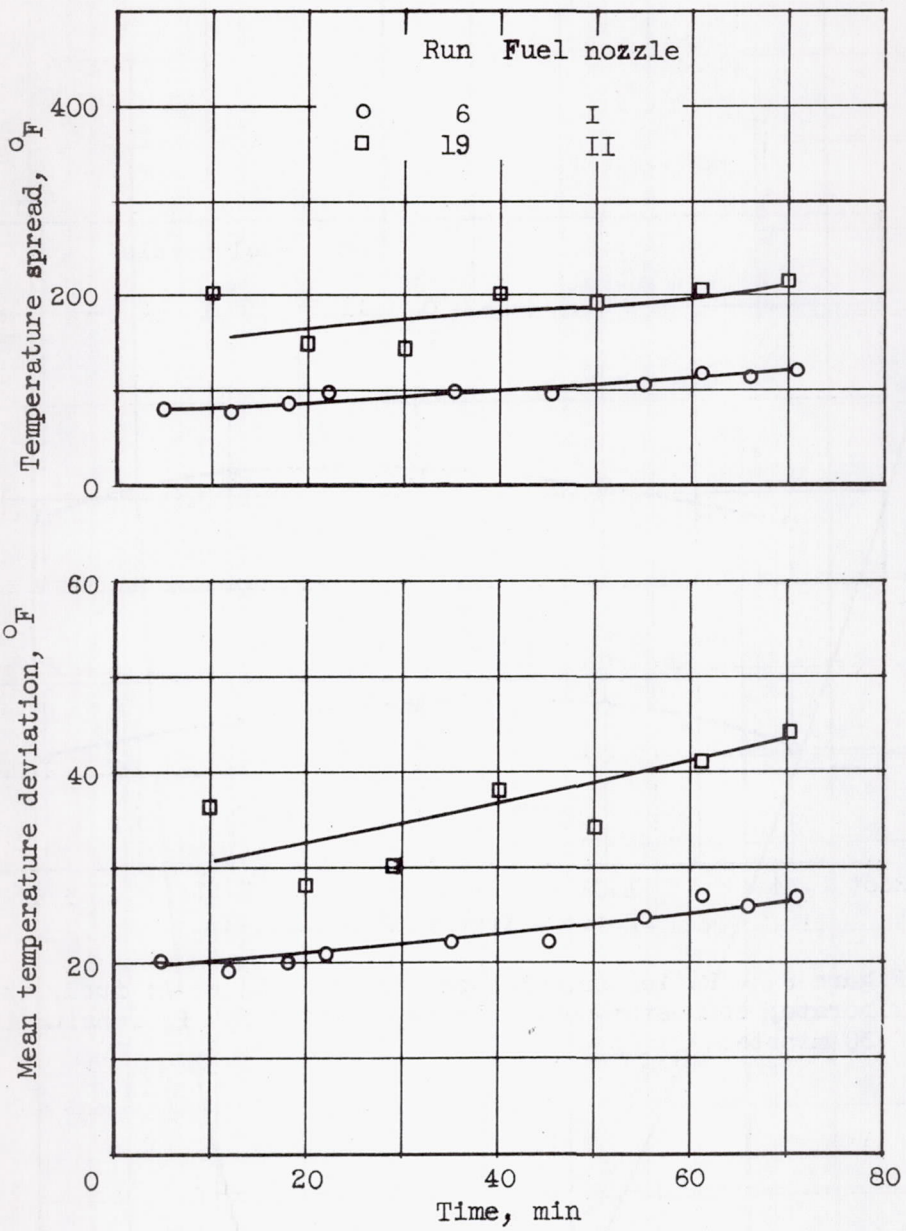


Figure 8. - Temperature spread and mean temperature deviation. Liner A; fuel, trimethyl borate; combustor-outlet temperature, 1550° F.

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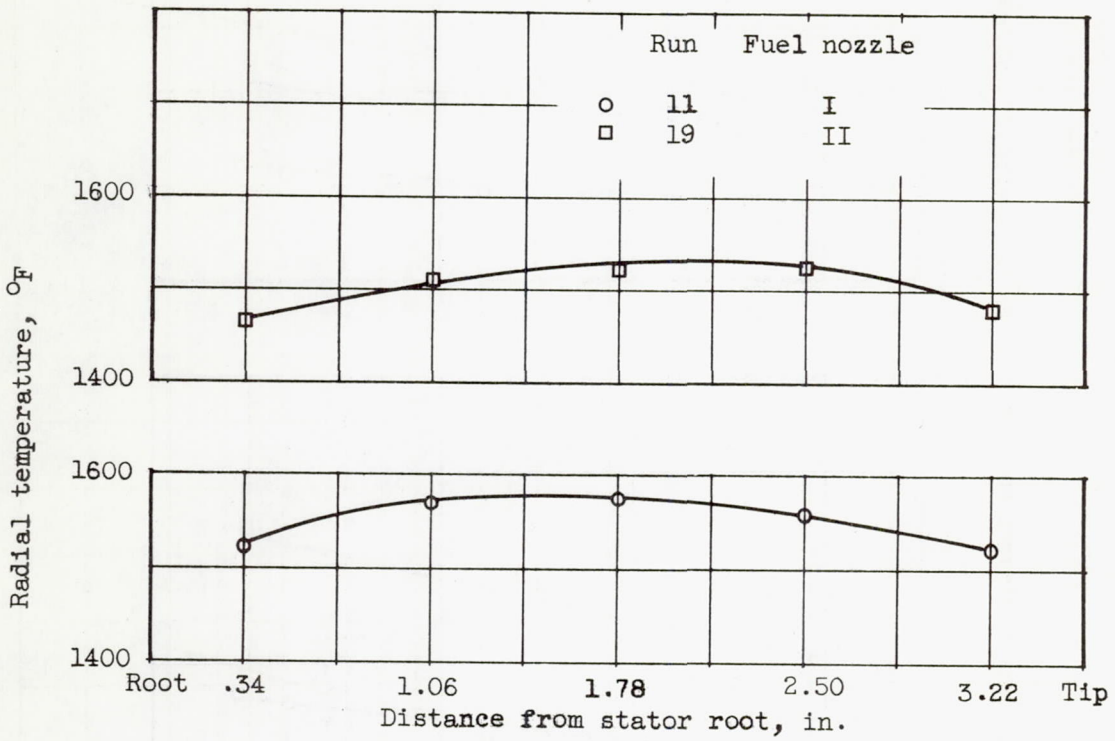


Figure 9. - Radial-temperature profile. Liner A; fuel, trimethyl borate; combustor-outlet temperature, 1550° F; running time, 30 minutes.

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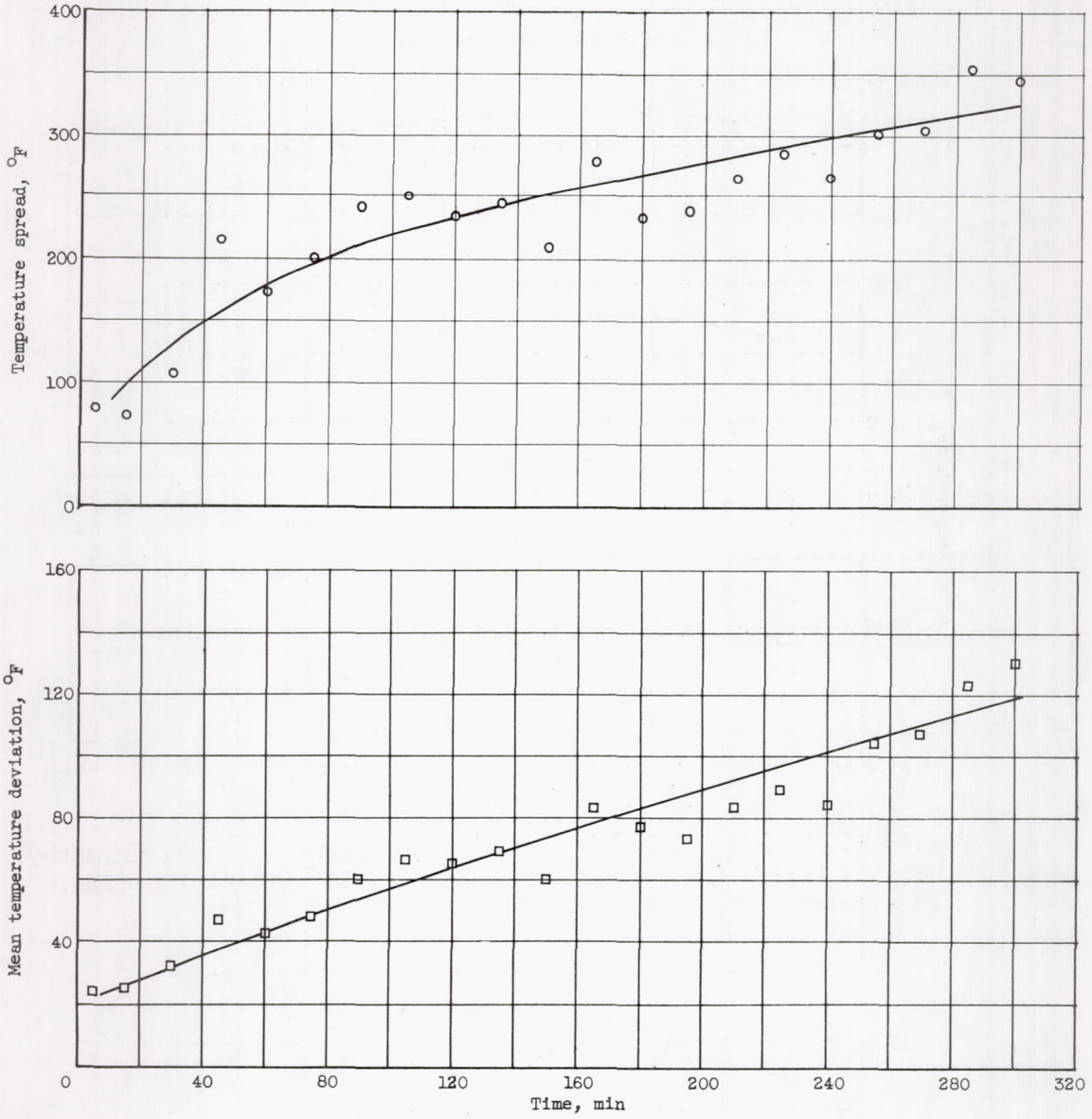


Figure 10. - Temperature spread and mean temperature deviation. Liner A; fuel nozzle I; fuel, trimethyl borate; combustor-outlet temperature 1550° F; run 11.

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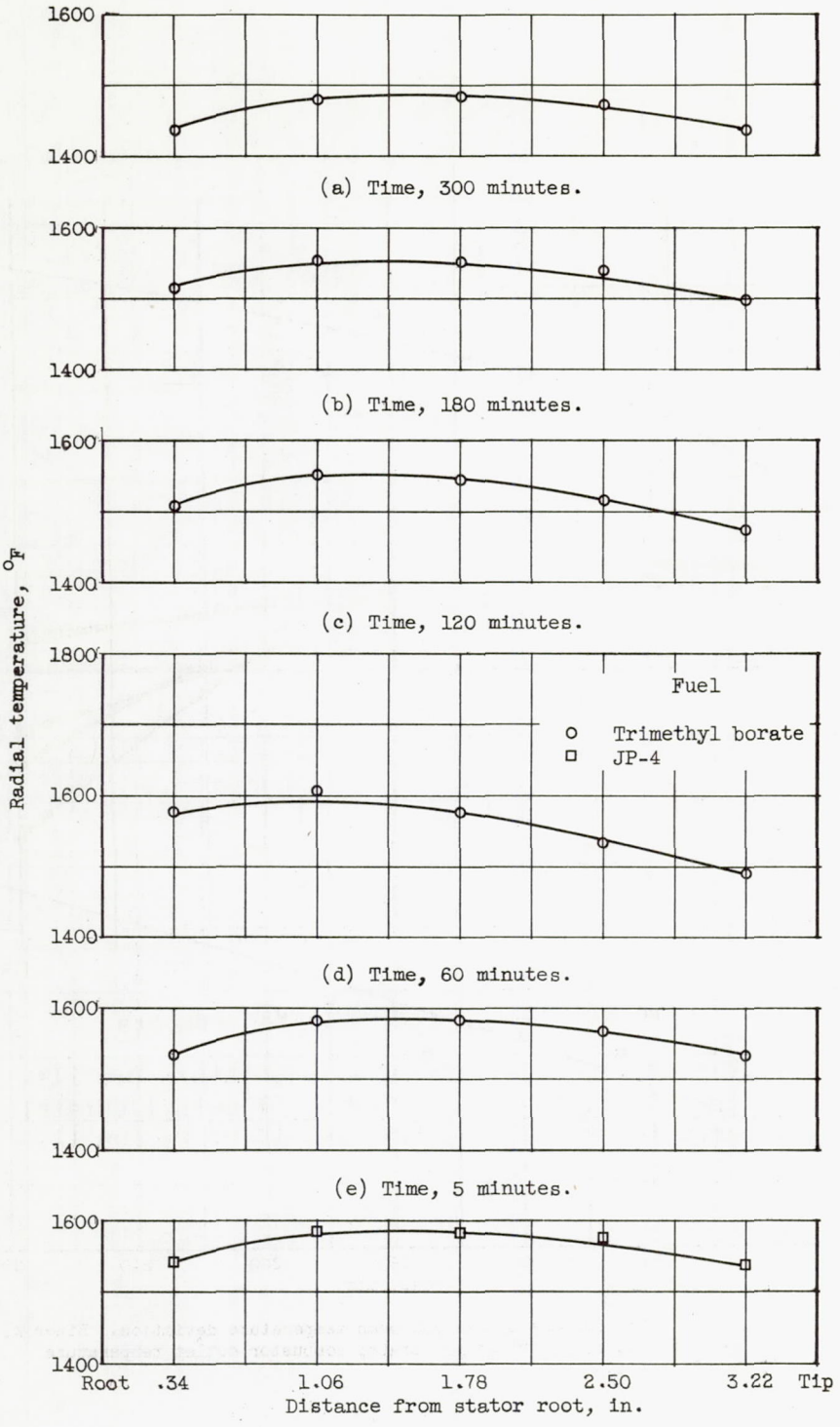


Figure 11. - Radial-temperature profile. Liner A; fuel nozzle I; combustor-outlet temperature, 1550° F; run 11.

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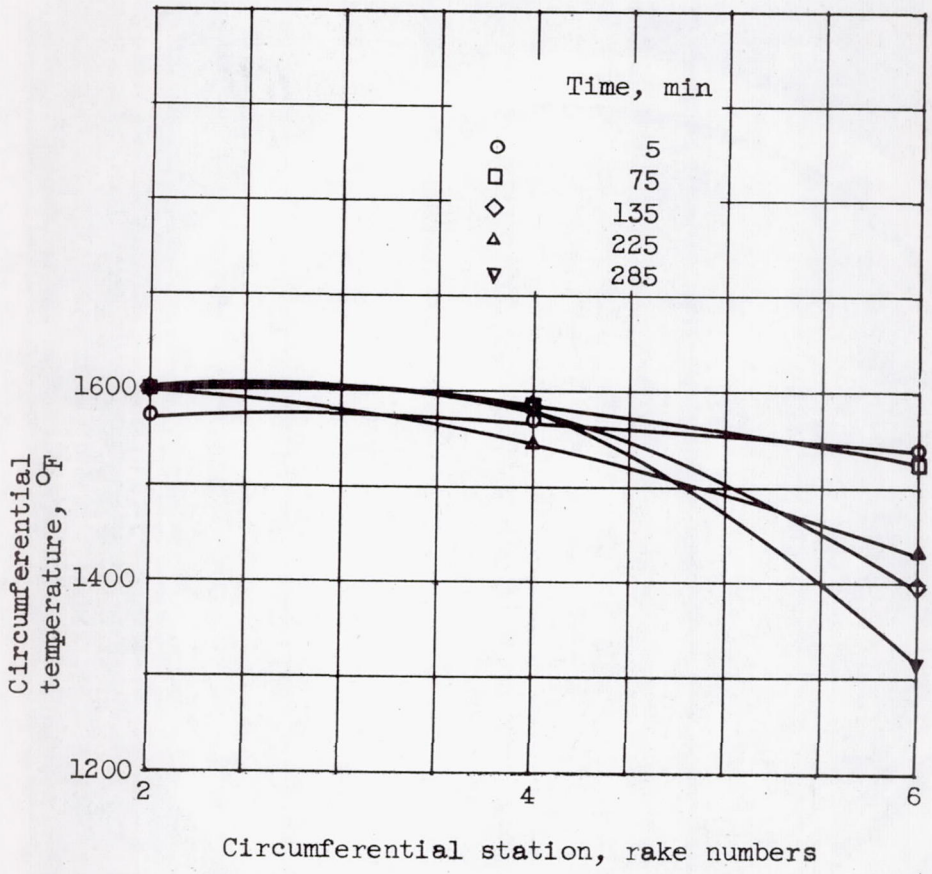
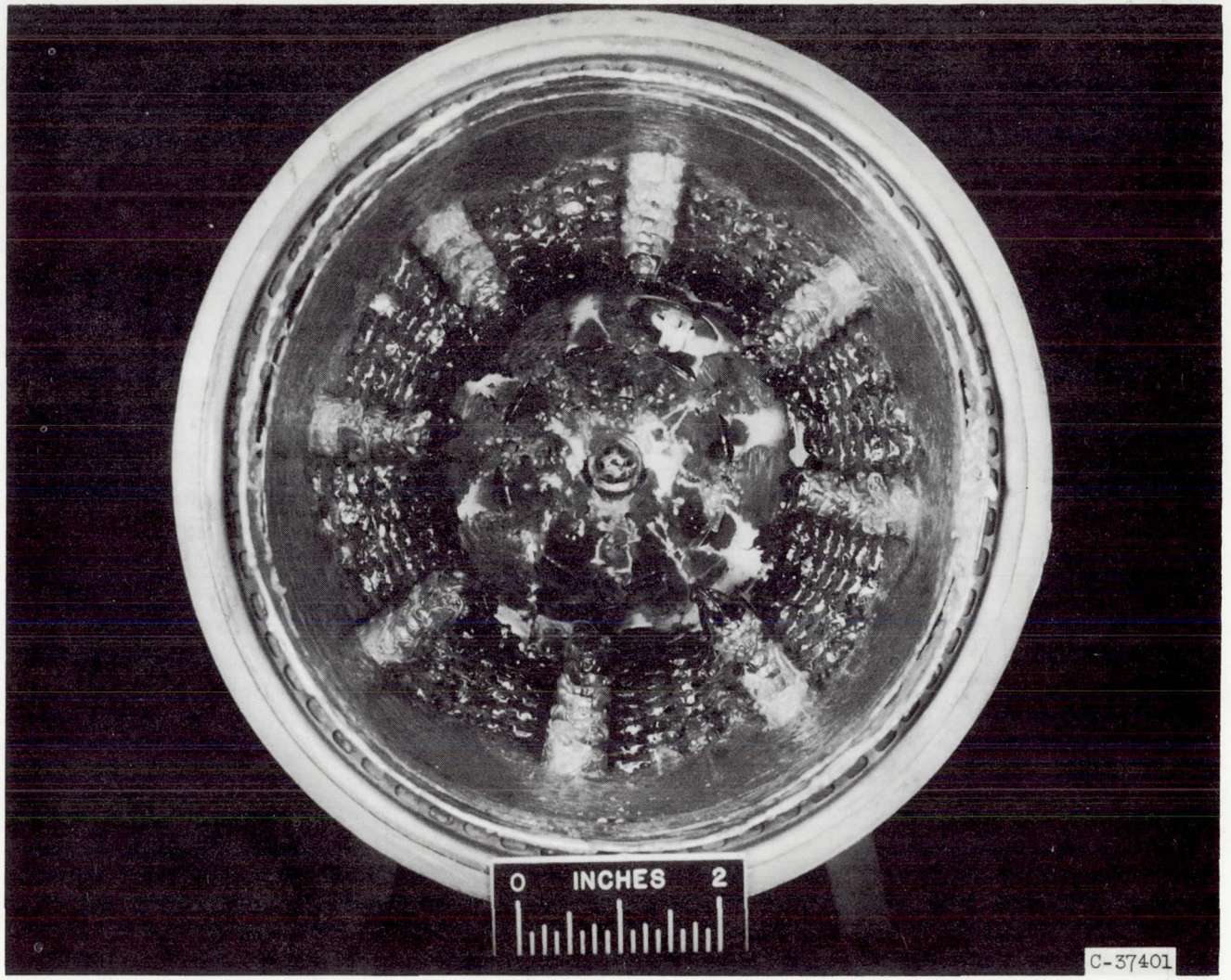


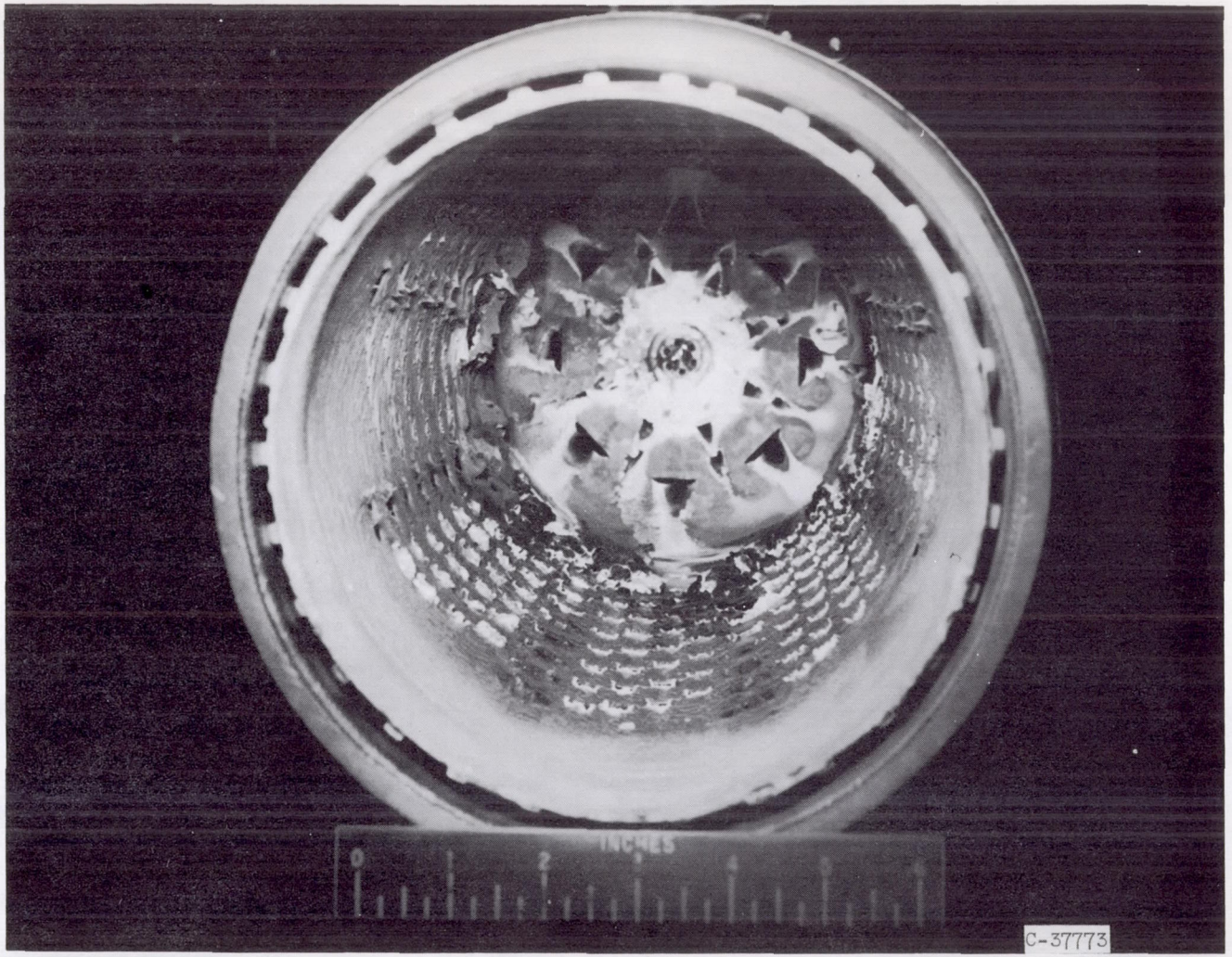
Figure 12. - Circumferential-temperature profile. Liner A; fuel nozzle I; fuel, trimethyl borate; combustor-outlet temperature, 1550° F; run 11.



(a) Liner with thimbles (A), run 6.

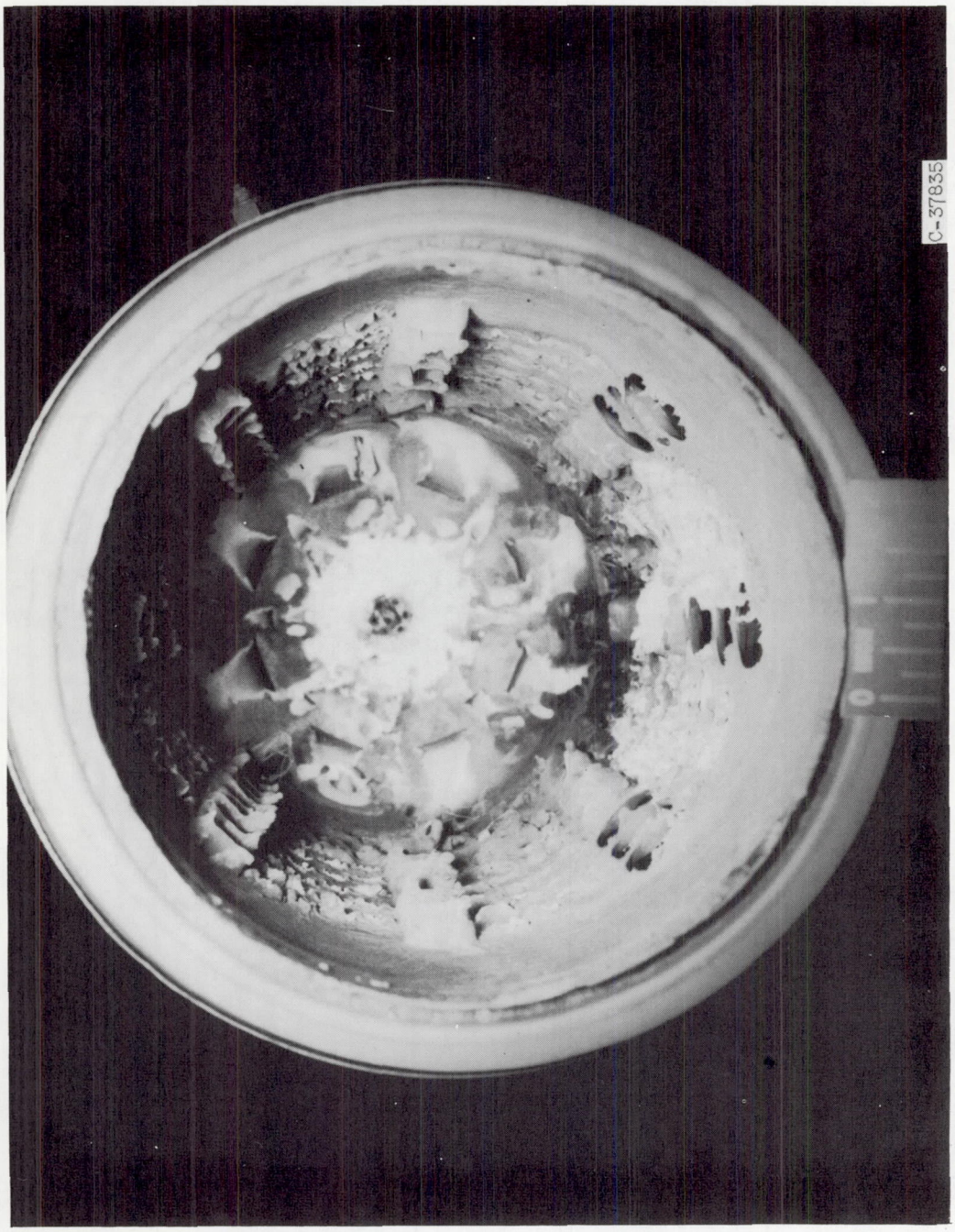
Figure 13. - Liner deposits after burning trimethyl borate at 1500° F for 70 minutes.

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(b) Liner without thimbles (B), run 18.

Figure 13. - Continued. Liner deposits after burning trimethyl borate at 1550° F for 70 minutes.



(c) Liner with nine enlarged holes (C), run 20.

Figure 13. - Concluded. Liner deposits after burning trimethyl borate at 1550° F for 70 minutes.

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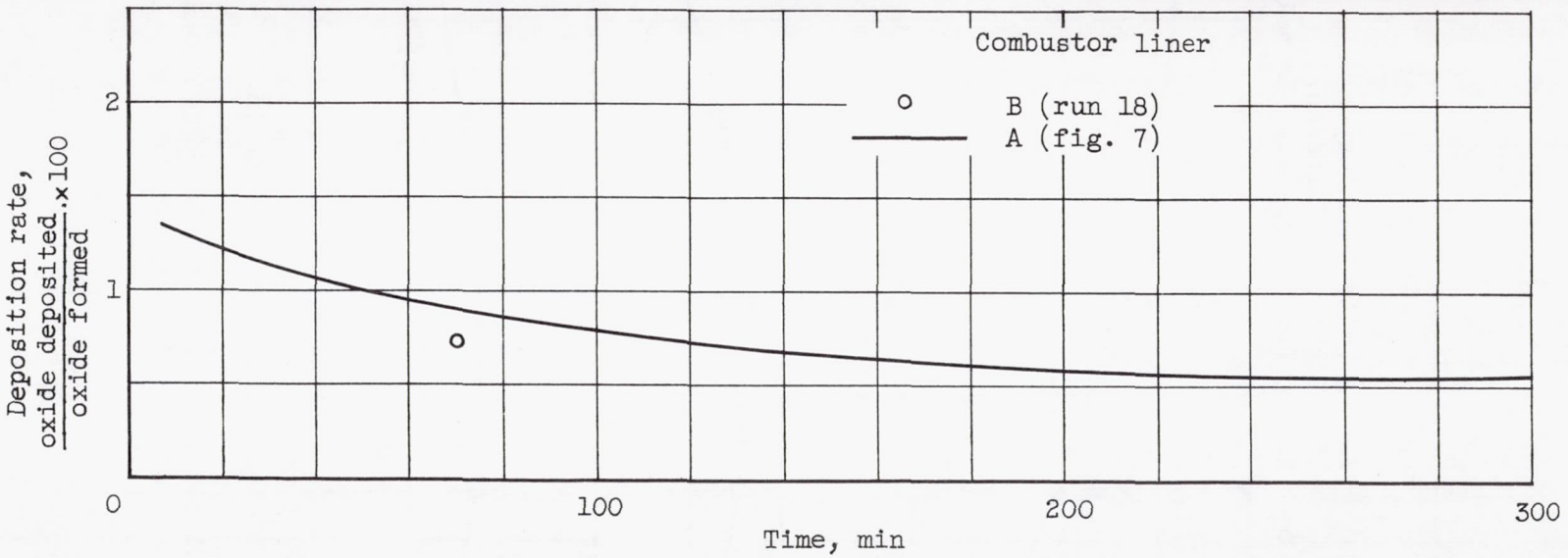


Figure 14. - Comparison of deposition rate for liners A and B. Fuel nozzle I; fuel, trimethyl borate; combustor-outlet temperature, 1550° F.

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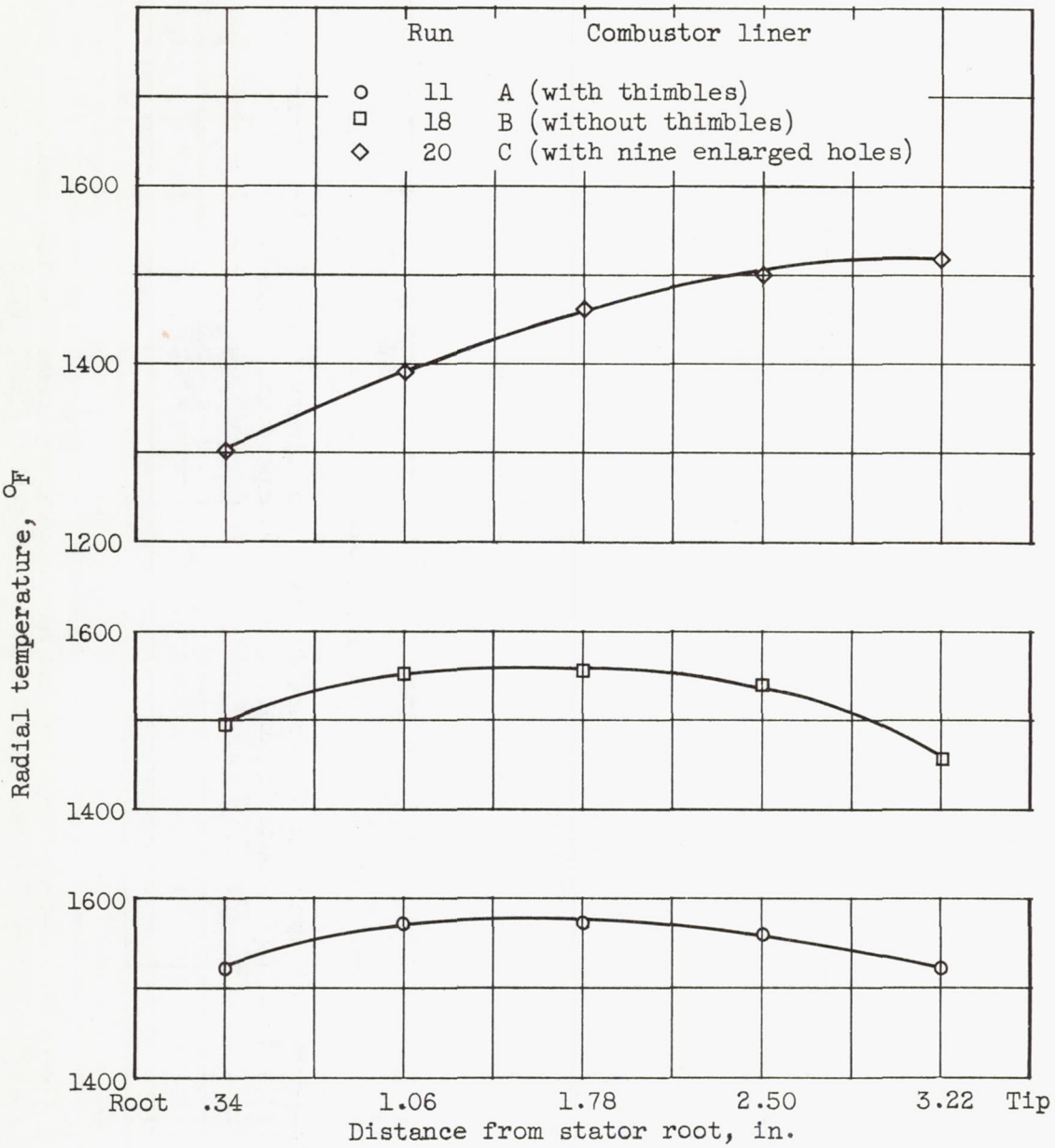


Figure 15. - Radial-temperature profile. Fuel nozzle I; fuel, trimethyl borate; combustor-outlet temperature, 1550° F; running time, 5 minutes.

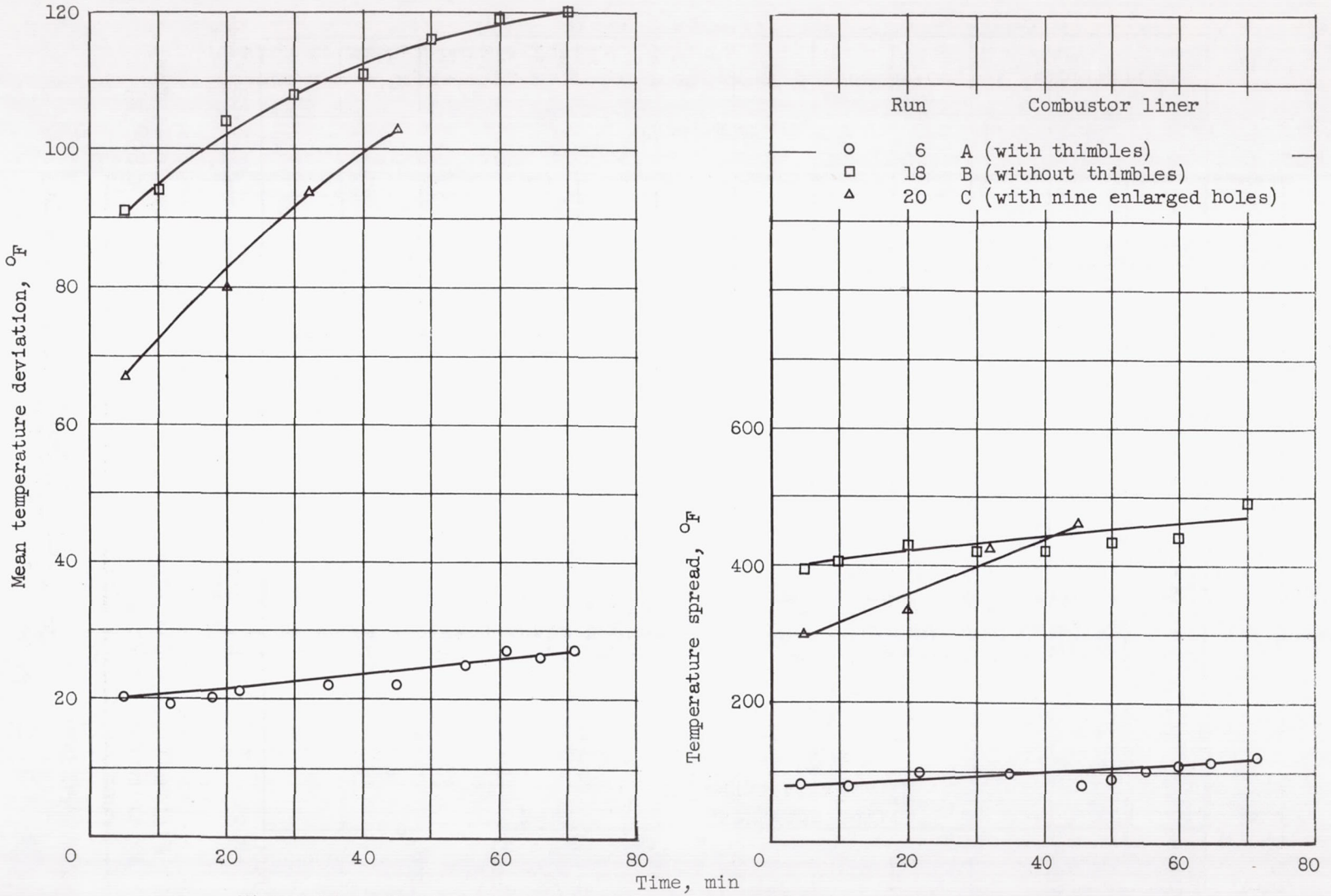


Figure 16. - Temperature spread and mean temperature deviation. Fuel nozzle I; fuel, trimthyl borate; combustor-outlet temperature, 1550° F.

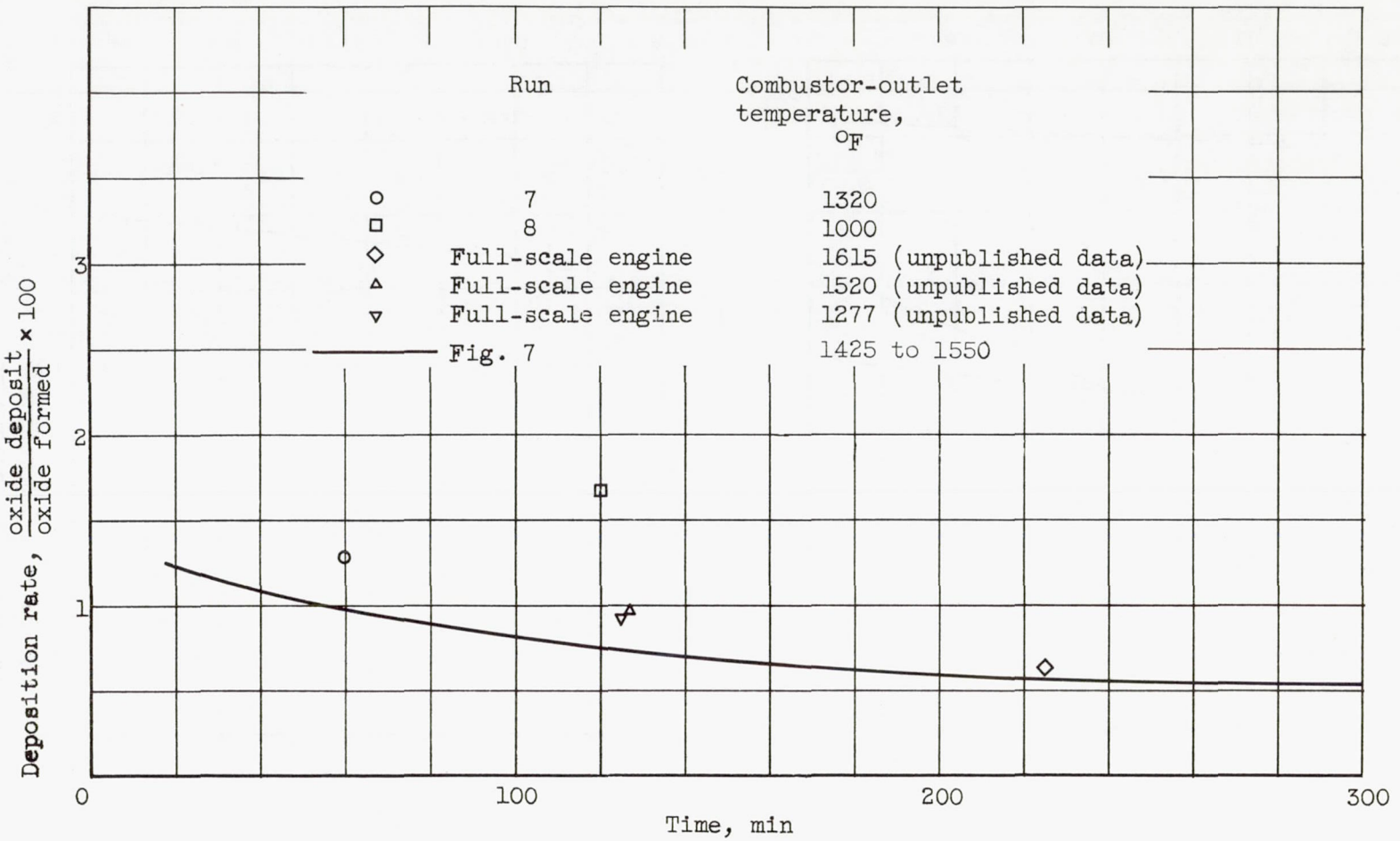


Figure 17. - Deposition rate for a range of combustor-outlet temperatures with trimethyl borate fuel.

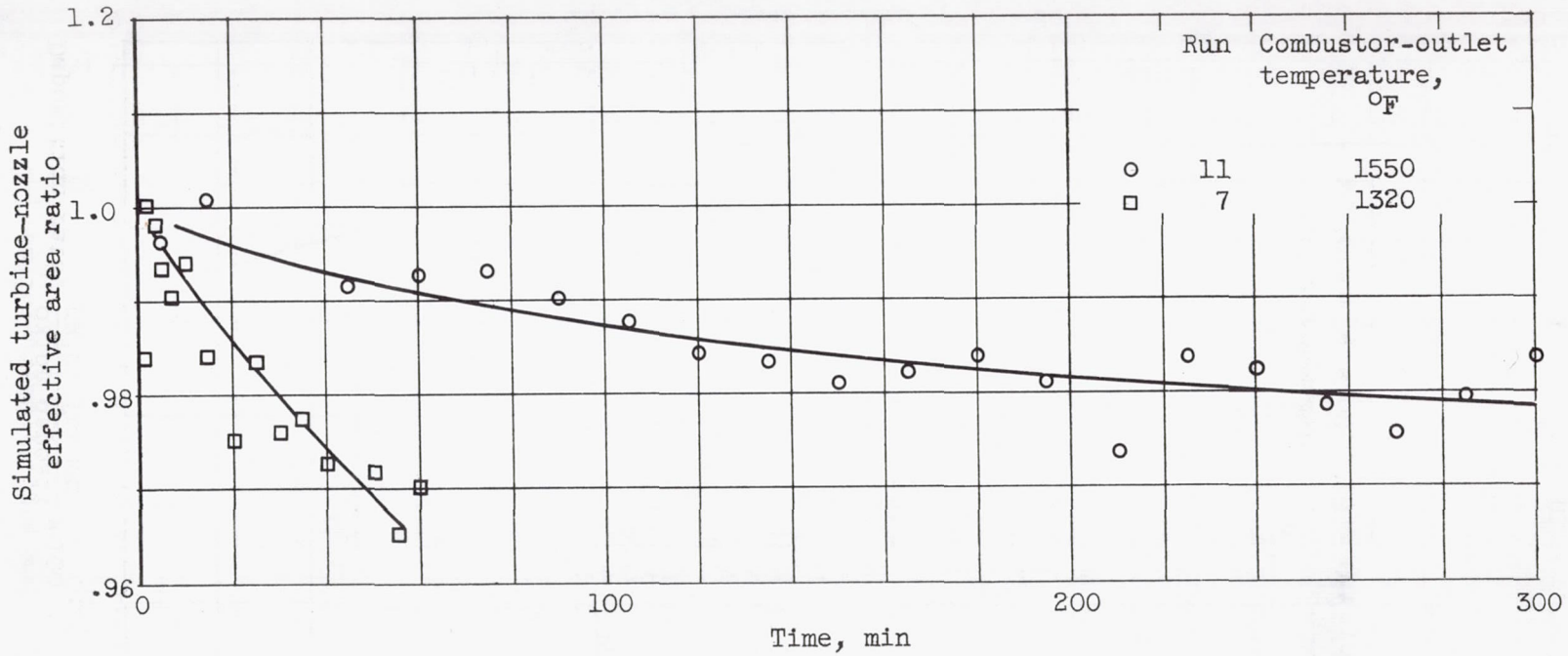
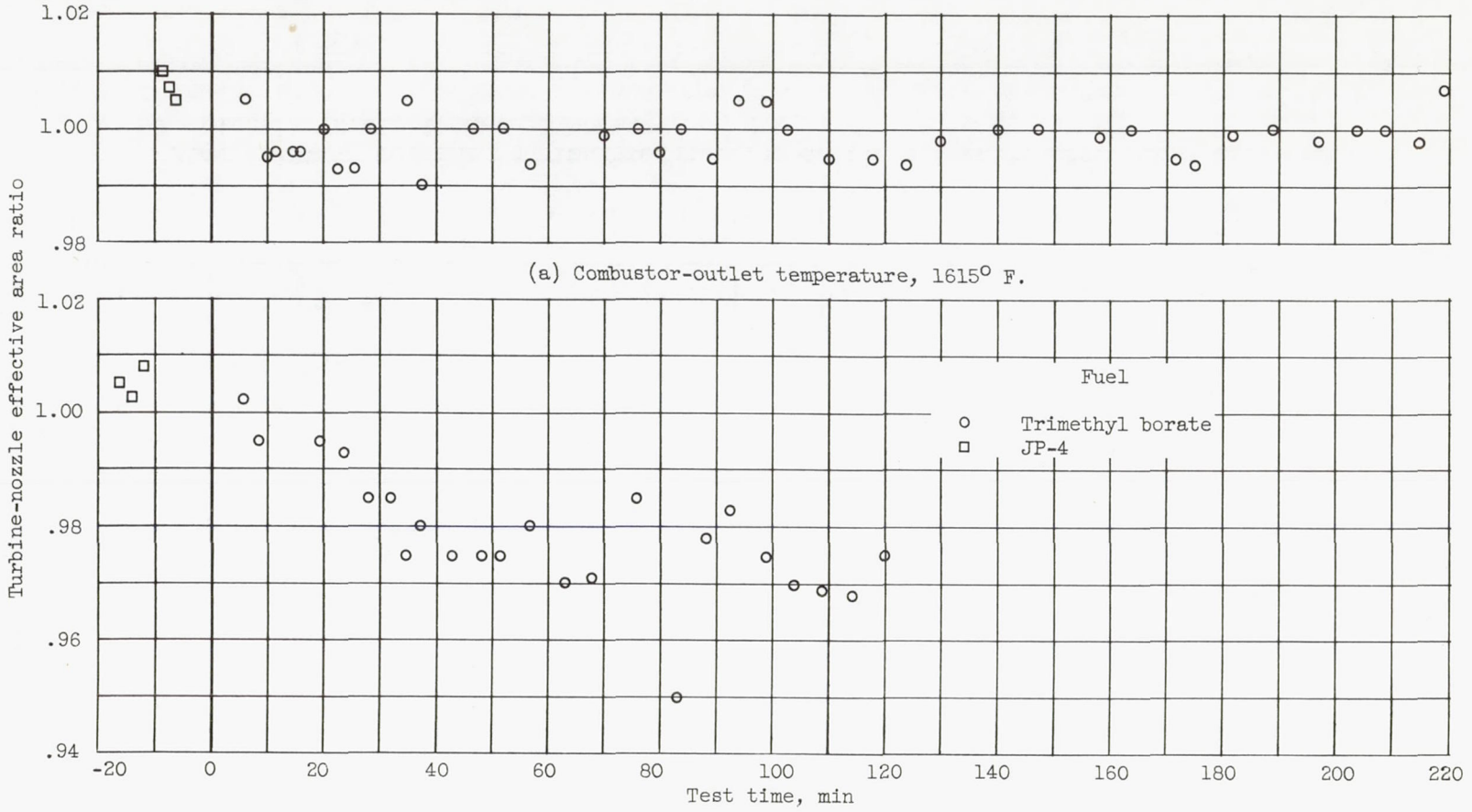


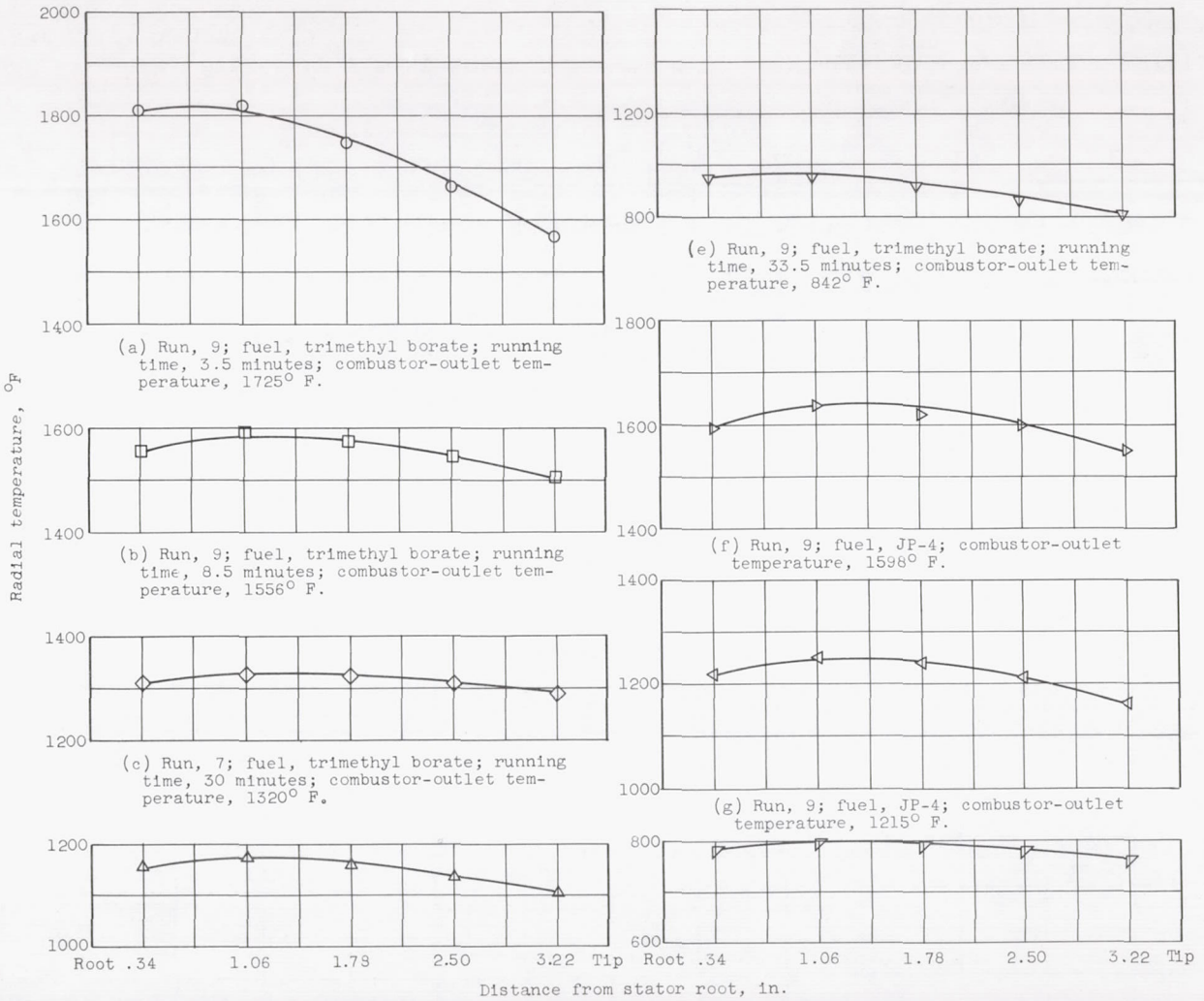
Figure 18. - Decrease in simulated turbine-nozzle effective area ratio with time. Liner A; fuel, trimethyl borate.



(a) Combustor-outlet temperature, 1615° F.

(b) Combustor-outlet temperature, 1277° F.

Figure 19. - Turbine-nozzle effective area ratio. Fuel, trimethyl borate; full-scale J47 engine (unpublished investigation).



(a) Run, 9; fuel, trimethyl borate; running time, 3.5 minutes; combustor-outlet temperature, 1725° F.

(b) Run, 9; fuel, trimethyl borate; running time, 8.5 minutes; combustor-outlet temperature, 1556° F.

(c) Run, 7; fuel, trimethyl borate; running time, 30 minutes; combustor-outlet temperature, 1320° F.

(d) Run, 9; fuel, trimethyl borate; running time, 23.5 minutes; combustor-outlet temperature, 1150° F.

(e) Run, 9; fuel, trimethyl borate; running time, 33.5 minutes; combustor-outlet temperature, 842° F.

(f) Run, 9; fuel, JP-4; combustor-outlet temperature, 1598° F.

(g) Run, 9; fuel, JP-4; combustor-outlet temperature, 1215° F.

(h) Run, 9; fuel, JP-4; combustor-outlet temperature, 786° F.

Figure 20. - Radial-temperature profile at various combustor-outlet temperatures. Liner A.

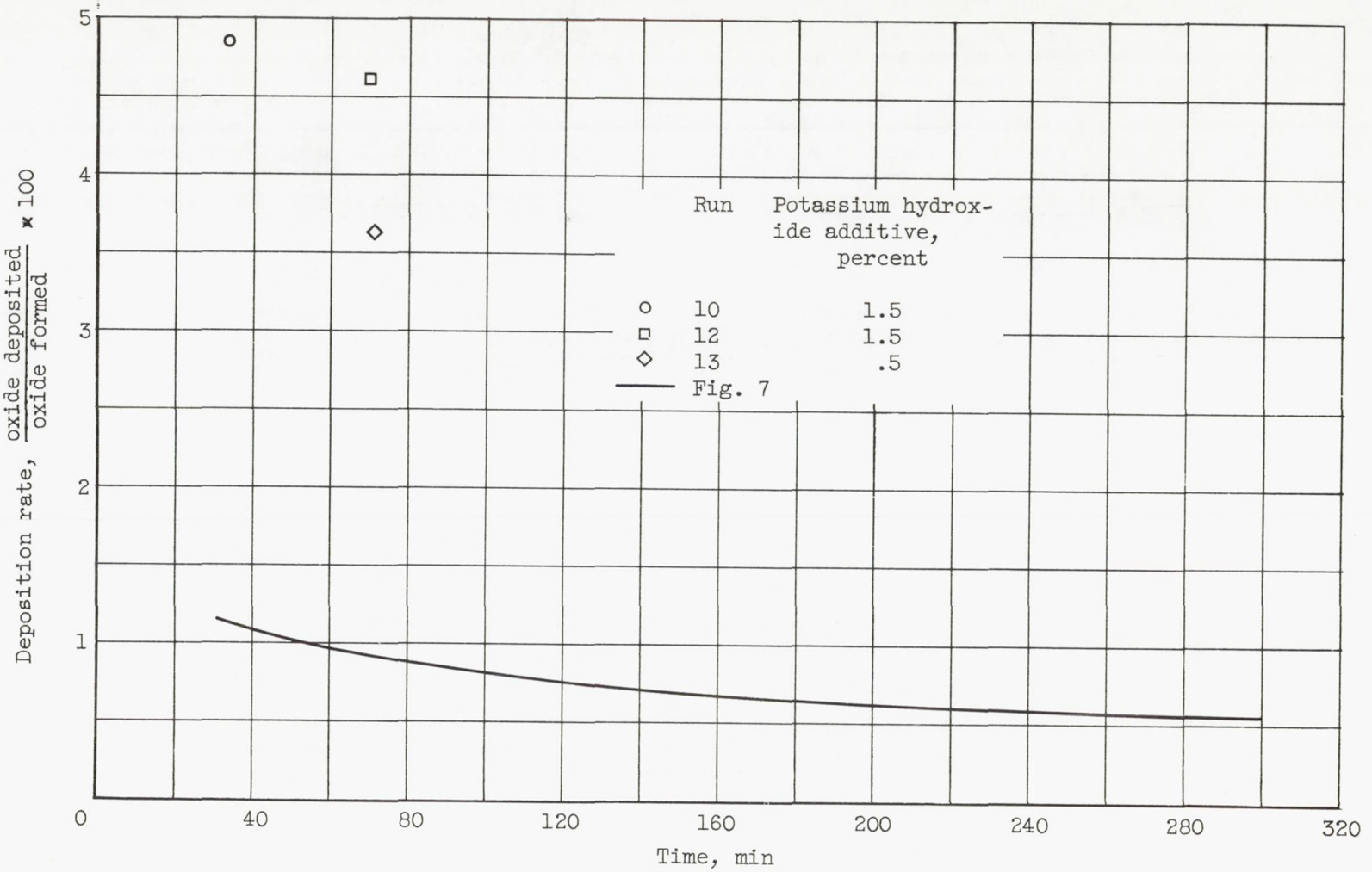
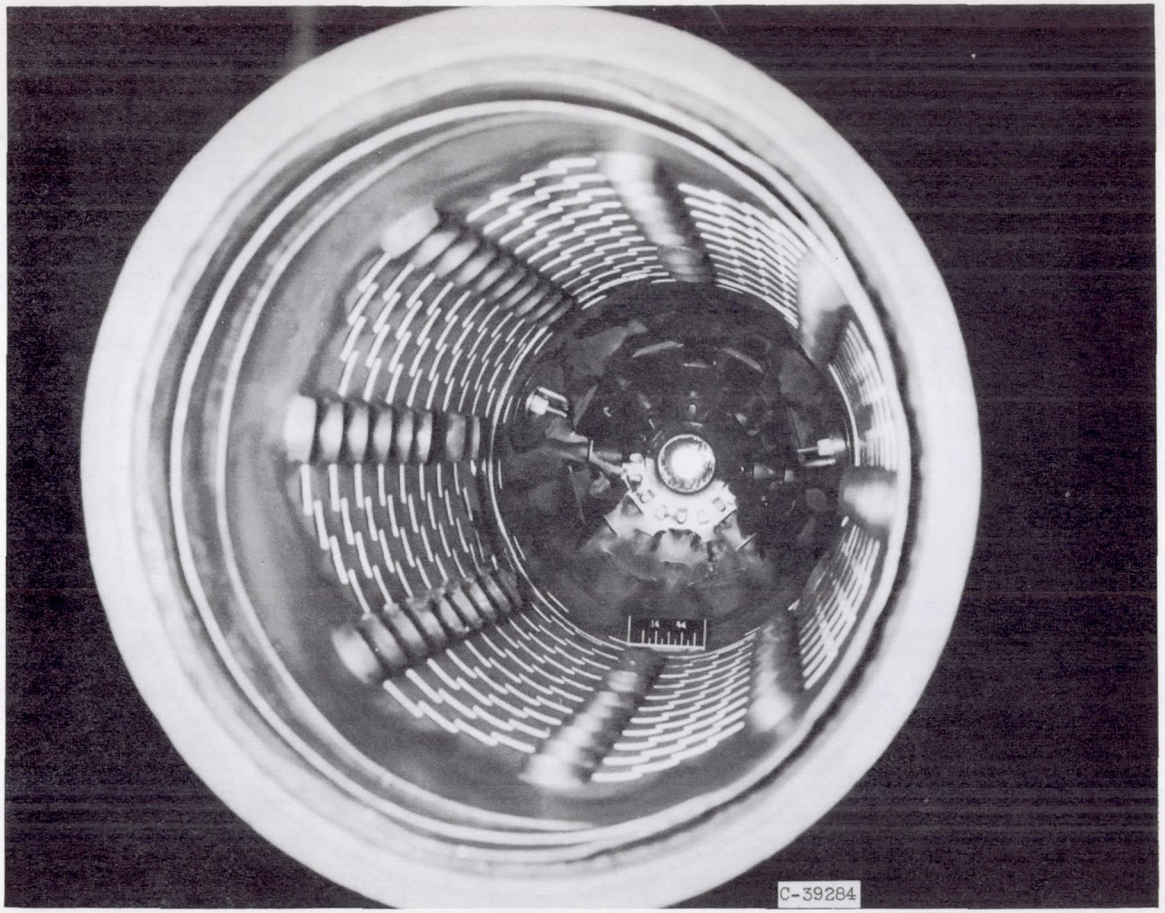


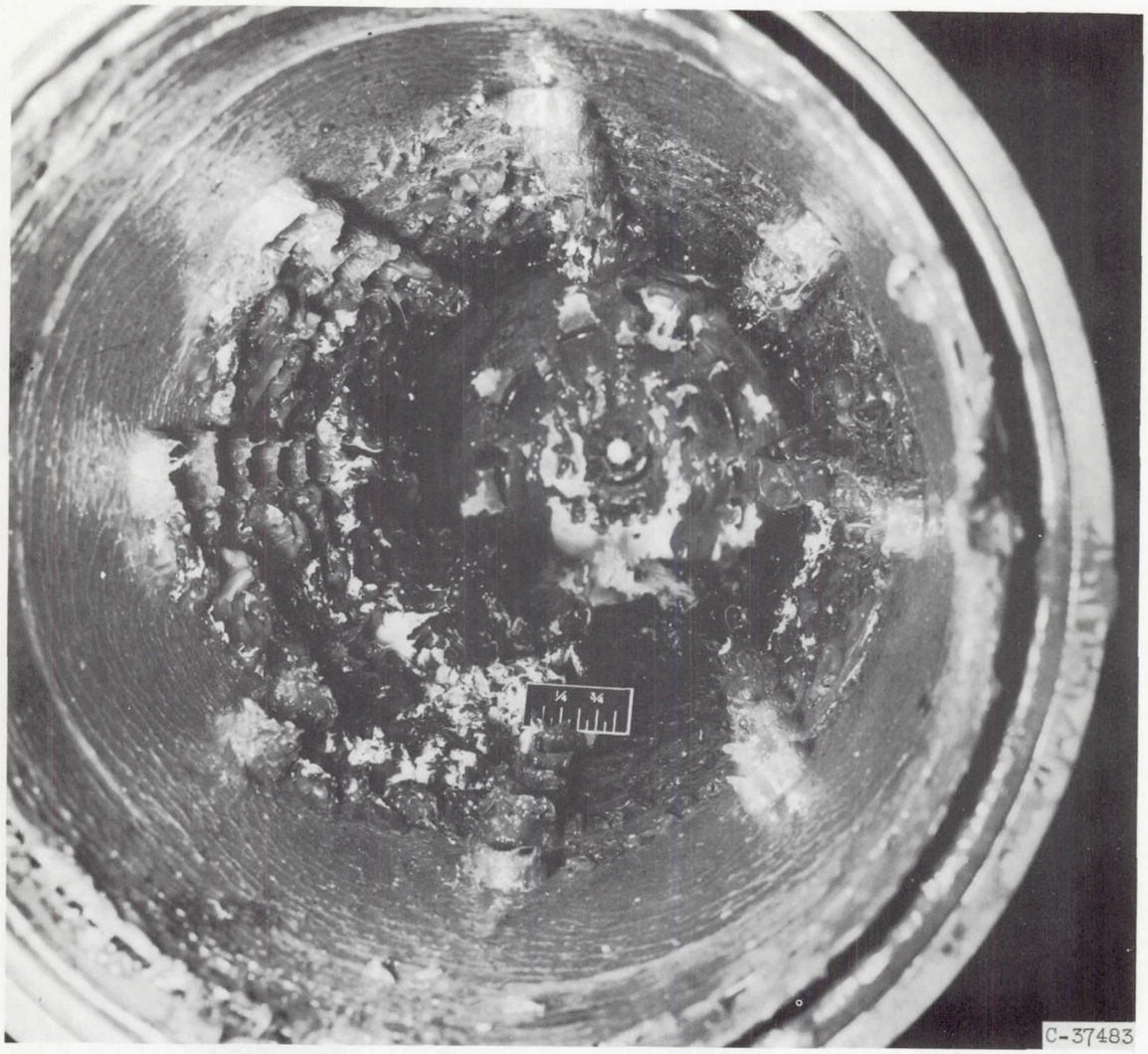
Figure 21. - Deposition rate of trimethyl borate fuel with potassium hydroxide additive. Liner A, fuel nozzle I.



(a) Liner, clean

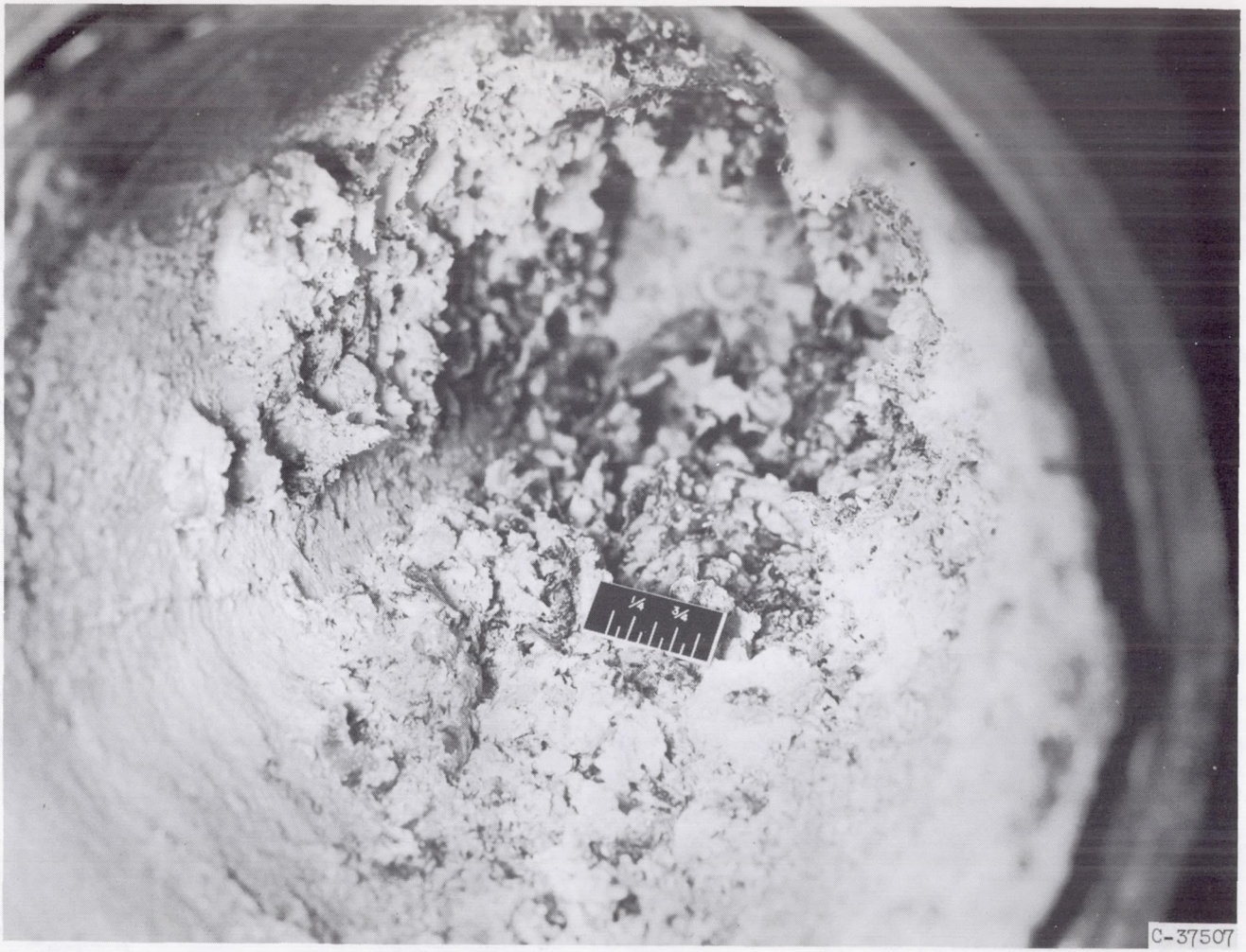
Figure 22. - Result of potassium hydroxide additive on deposition in combustor liner, transition section, and simulated turbine-nozzle section.

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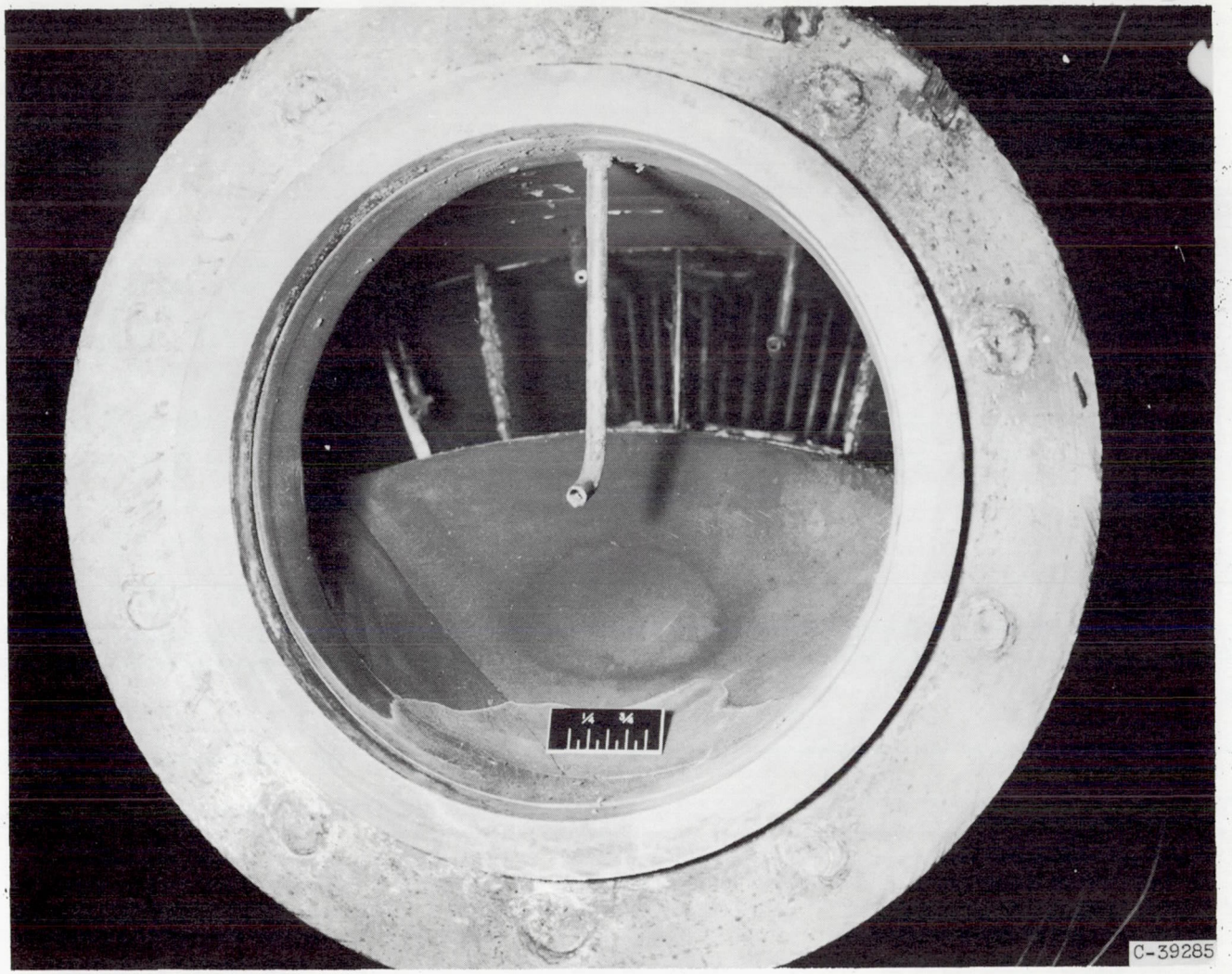
(b) Liner, after 5 hours operation. Fuel, trimethyl borate; combustor-outlet temperature, 1550° F.

Figure 22. - Continued. Result of potassium hydroxide additive on deposition in combustor liner, transition section, and simulated turbine-nozzle section.



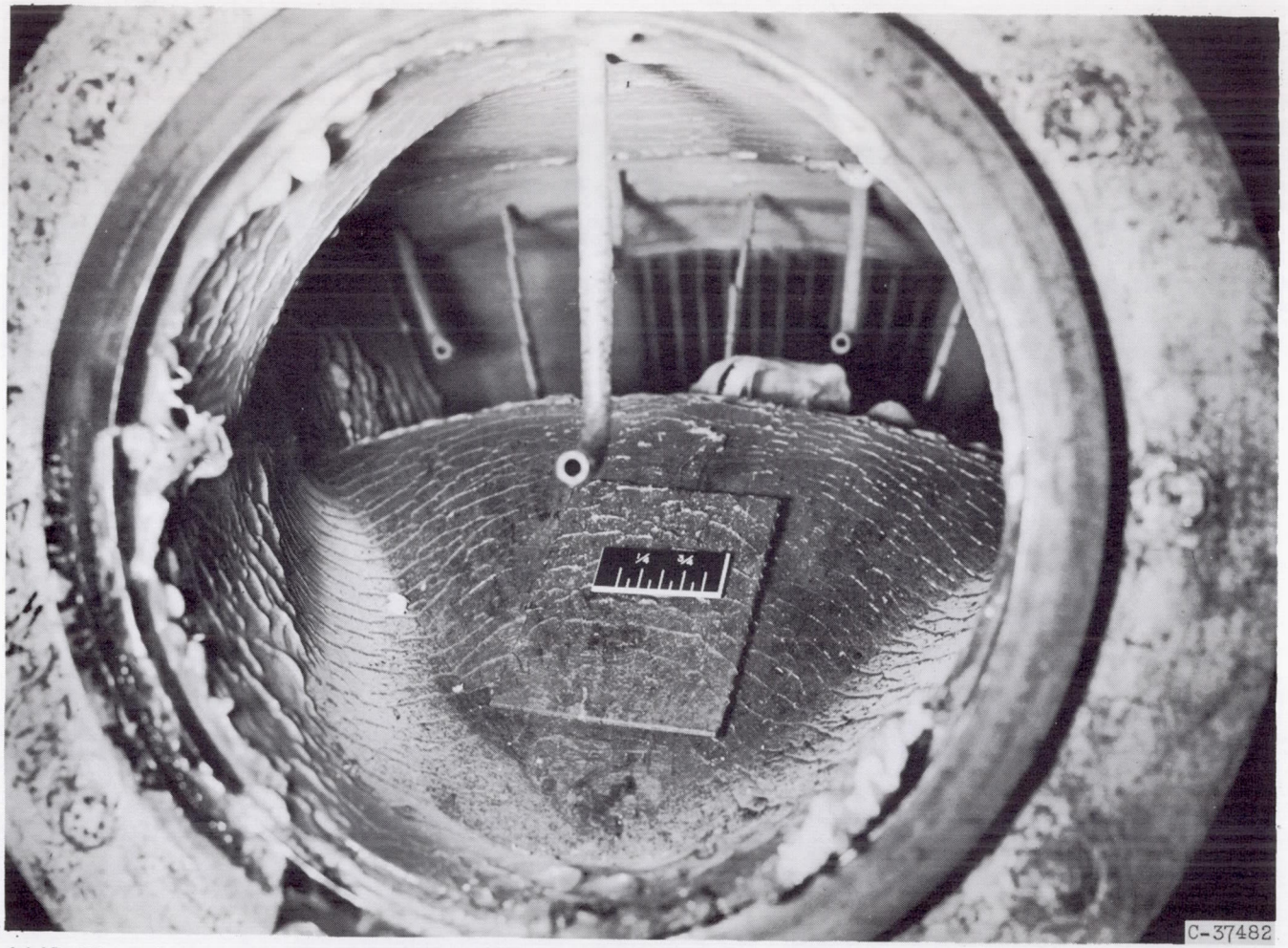
(c) Liner, after 70 minutes operation. Fuel, trimethyl borate plus 1.5 percent potassium hydroxide; combustor-outlet temperature, 1550° F.

Figure 22. - Continued. Result of potassium hydroxide additive on deposition in combustor liner, transition section, and simulated turbine-nozzle section.



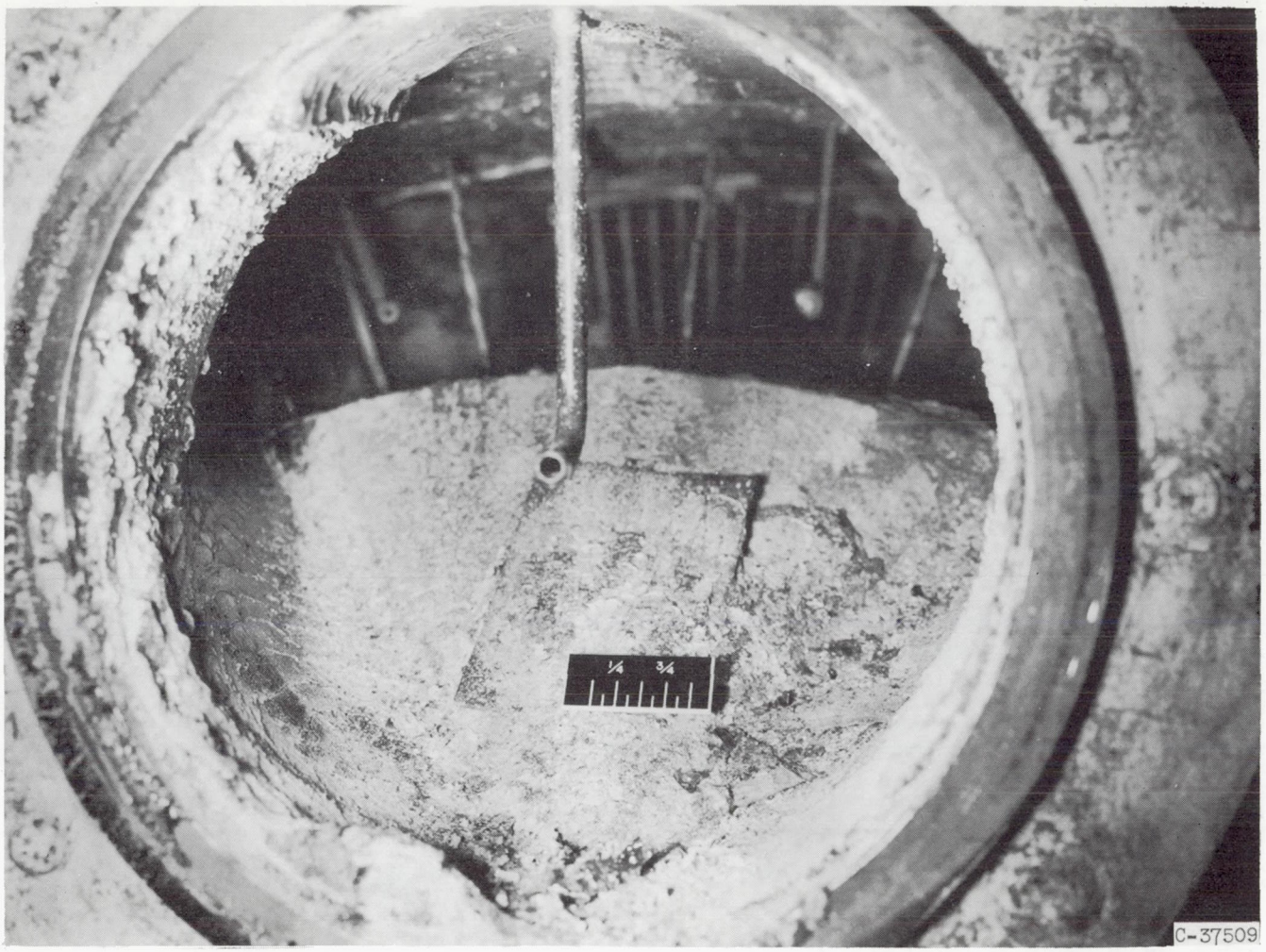
(d) Transition section, clean.

Figure 22. - Continued. Result of potassium hydroxide additive on deposition in combustor liner, transition section, and simulated turbine-nozzle section.



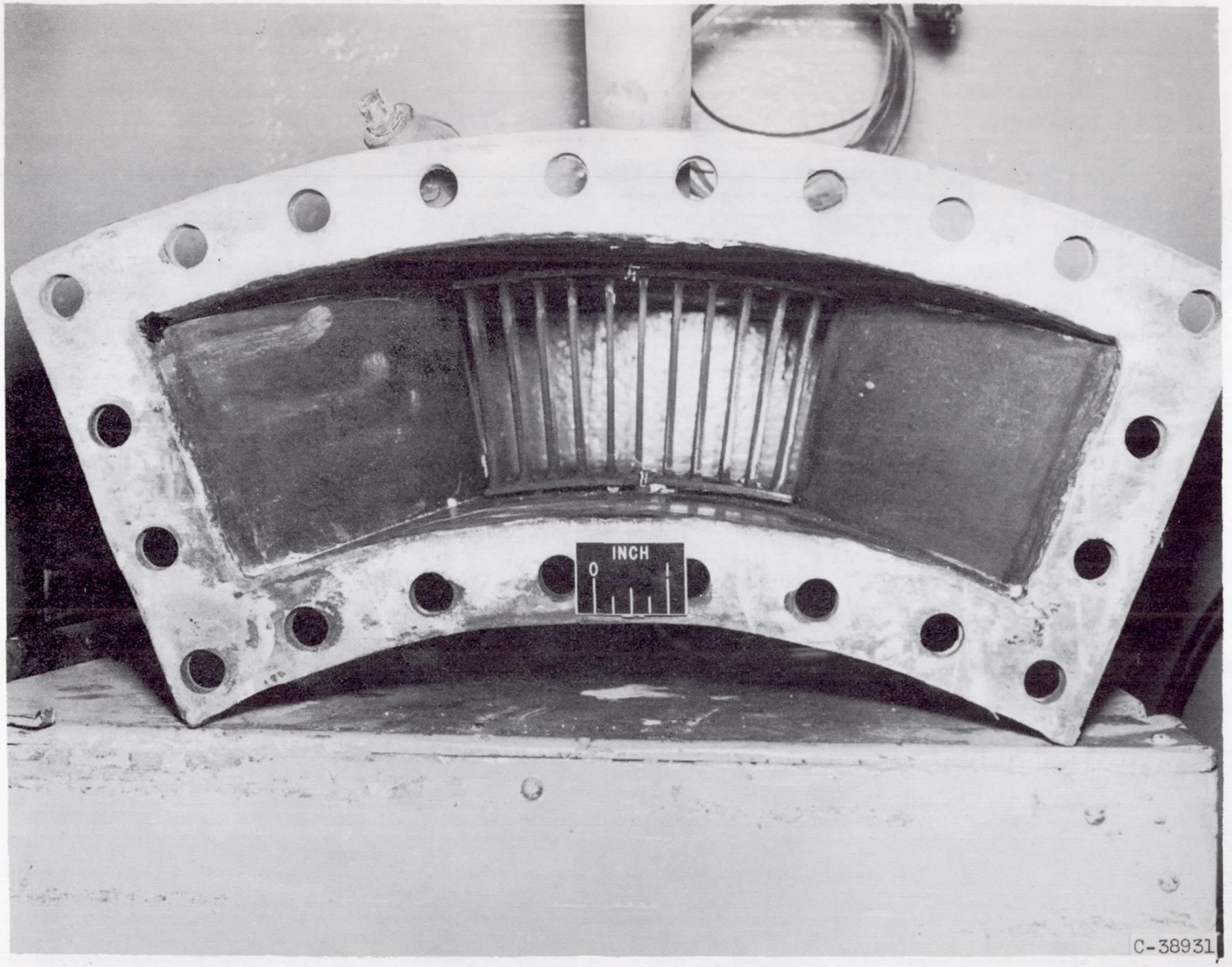
(e) Transition section, after 5 hours operation. Fuel, trimethyl borate; combustor-outlet temperature, 1550° F.

Figure 22. - Continued. Result of potassium hydroxide additive on deposition in combustor liner, transition section, and simulated turbine-nozzle section.



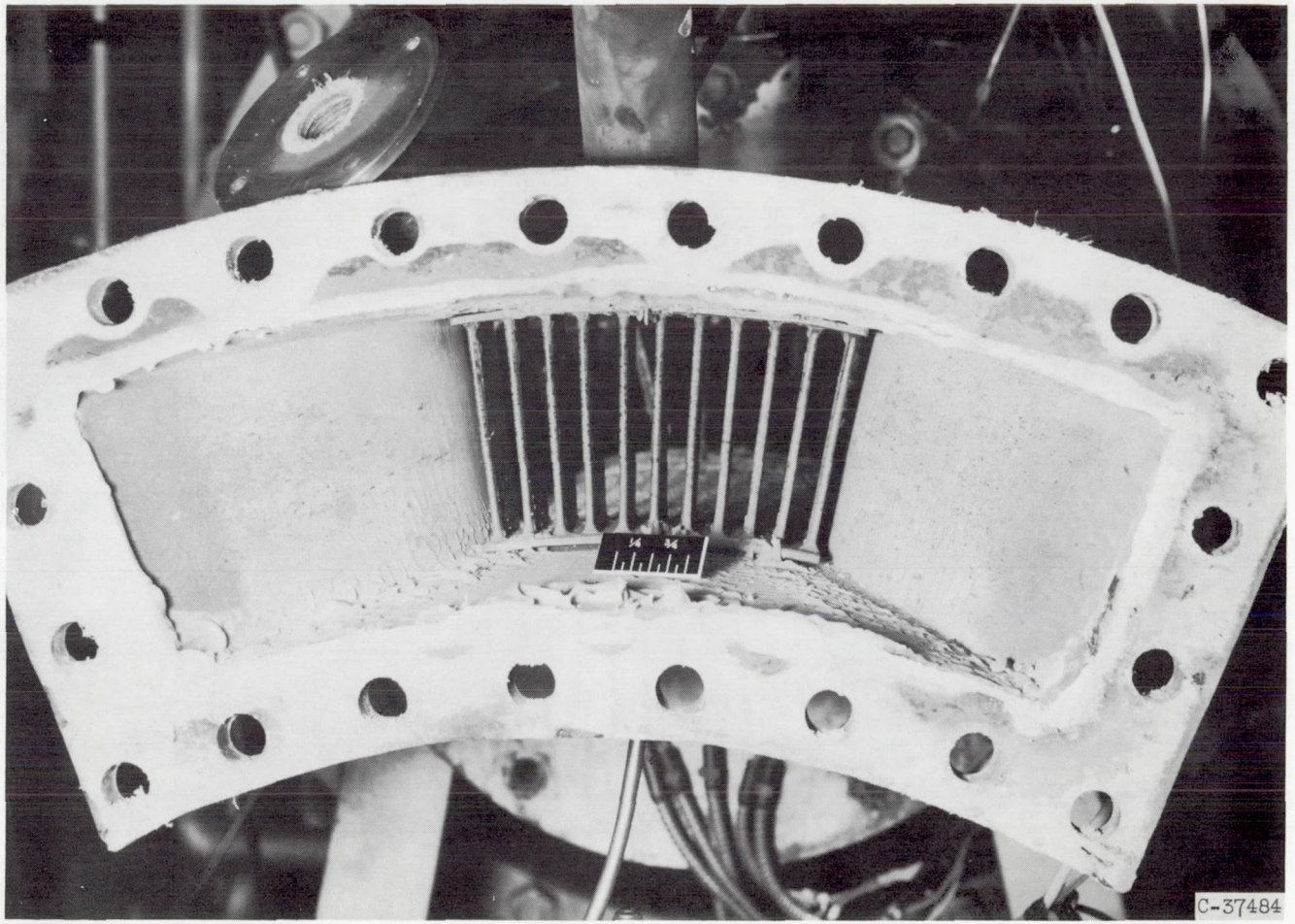
(f) Transition section, after 70 minutes operation. Fuel, trimethyl borate plus 1.5 percent potassium hydroxide; combustor-outlet temperature, 1550° F.

Figure 22. - Continued. Result of potassium hydroxide additive on deposition in combustor liner, transition section, and simulated turbine-nozzle section.



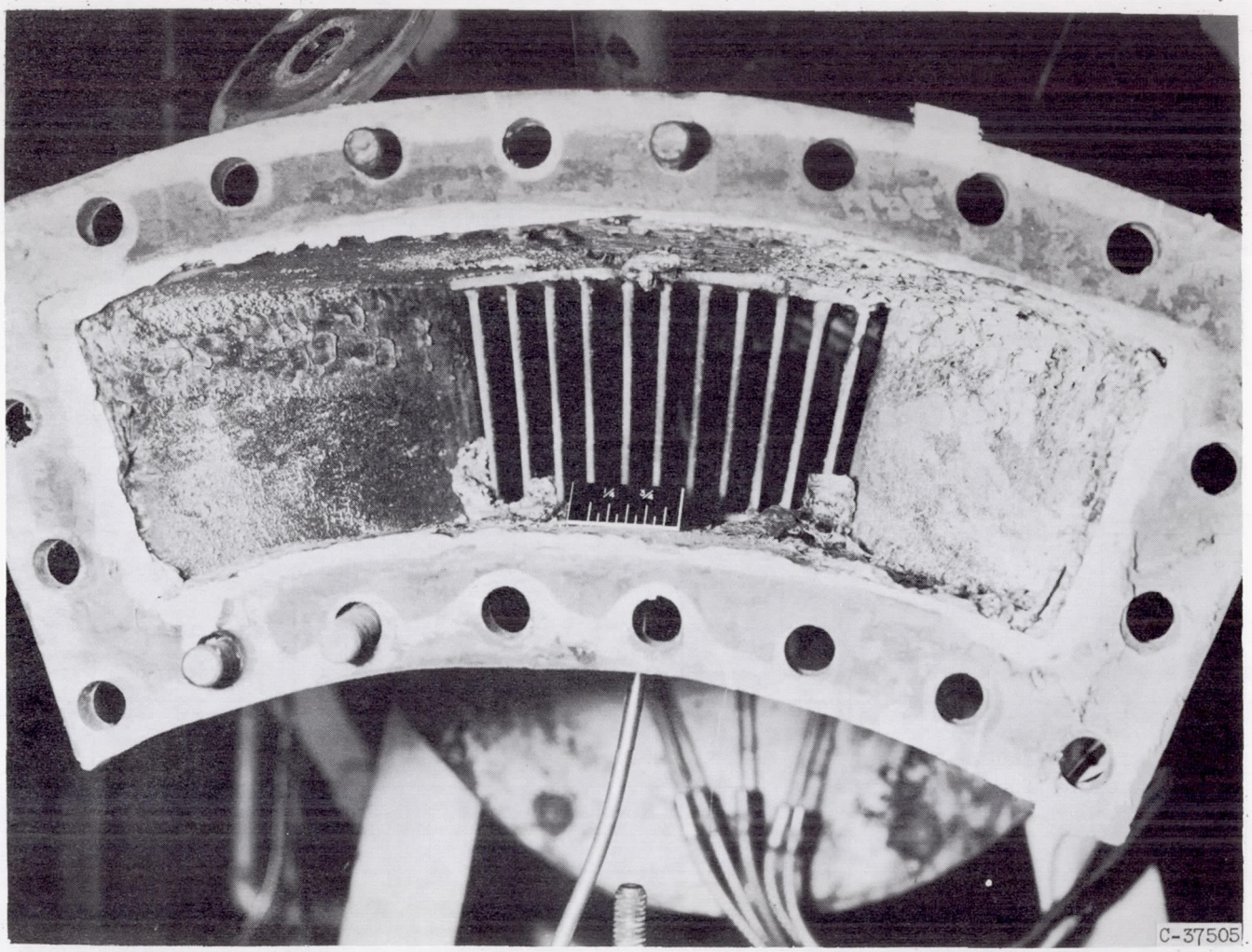
(g) Simulated turbine-nozzle section, clean.

Figure 22. - Continued. Result of potassium hydroxide additive on deposition in combustor liner, transition section, and simulated turbine-nozzle section.



(h) Simulated turbine-nozzle section, after 5 hours operation. Fuel, trimethyl borate; combustor-outlet temperature, 1550° F.

Figure 22. - Continued. Result of potassium hydroxide additive on deposition in combustor liner, transition section, and simulated turbine-nozzle section.



(i) Simulated turbine-nozzle section, after 70 minutes operation. Fuel, trimethyl borate plus 1.5 percent potassium hydroxide; combustor-outlet temperature, 1550° F.

Figure 22. - Concluded. Result of potassium hydroxide additive on deposition in combustor liner, transition section, and simulated turbine-nozzle section.

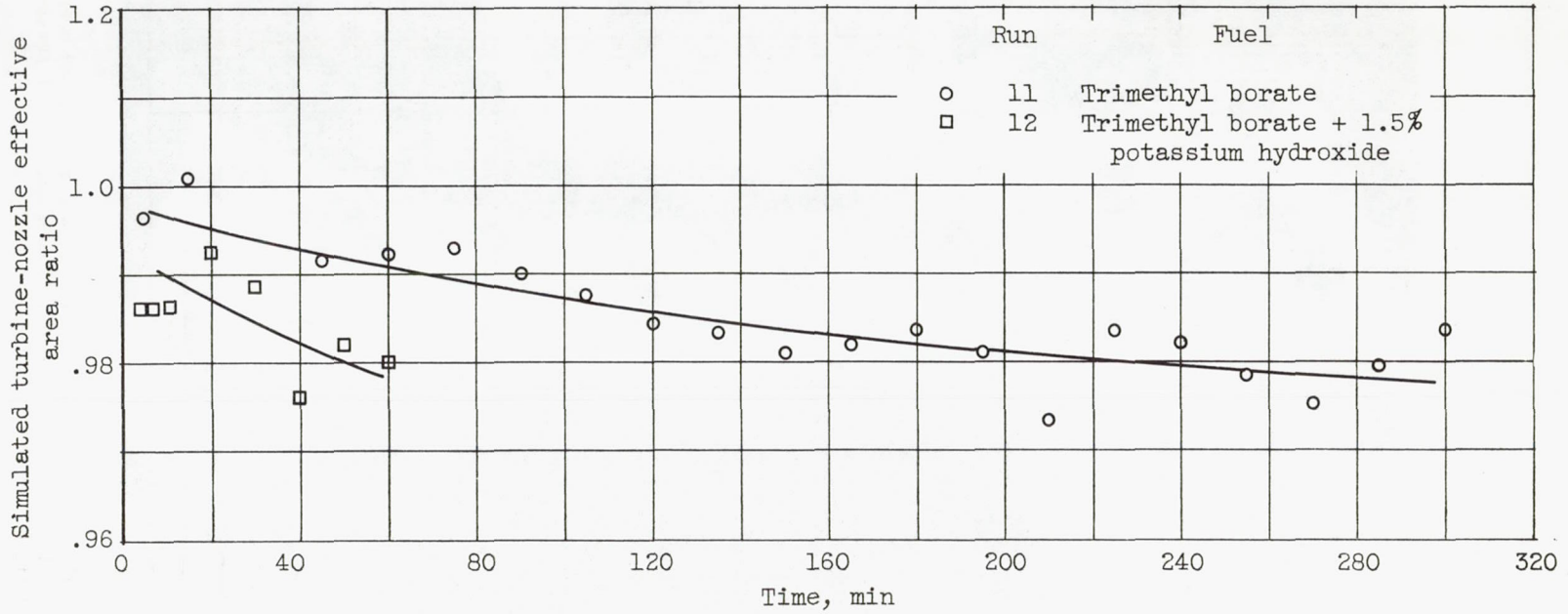


Figure 23. - Decrease in simulated turbine-nozzle effective area ratio for trimethyl borate fuel with and without potassium hydroxide additive. Combustor-outlet temperature, 1550° F.

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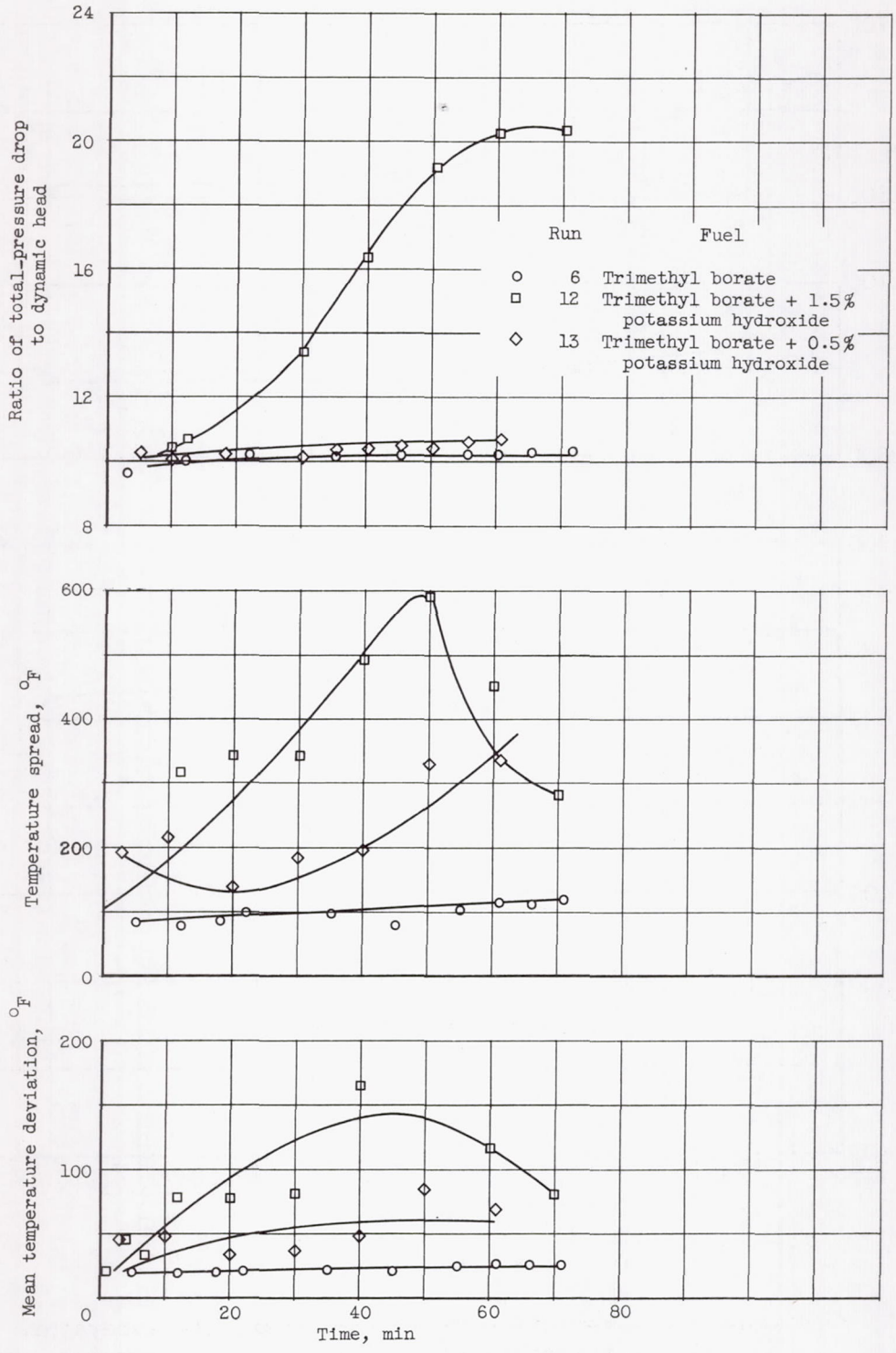


Figure 24. - Combustor pressure drop, temperature spread, and mean temperature deviation for trimethyl borate fuel with and without potassium hydroxide additive.

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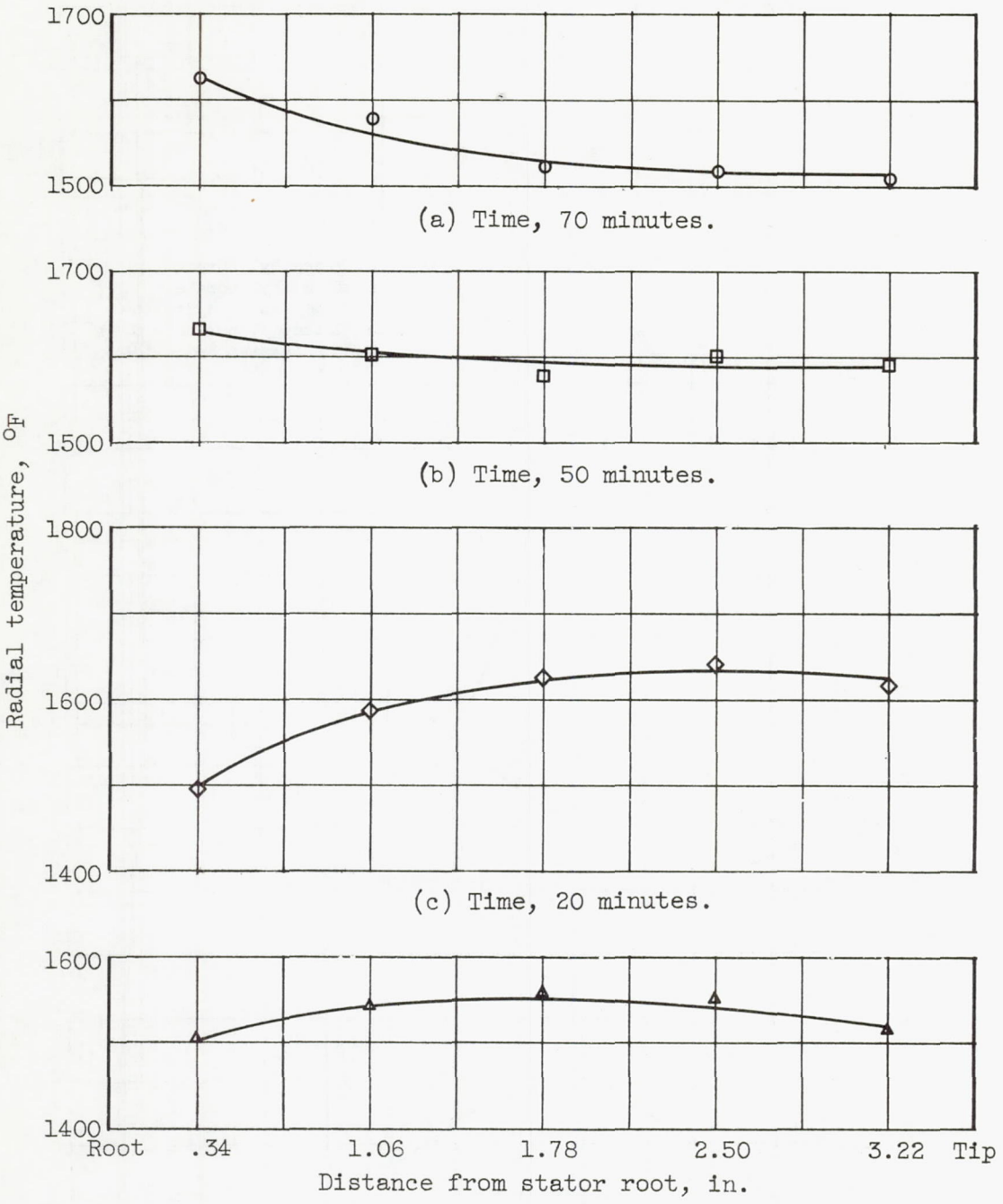


Figure 25. - Variation with time of radial-temperature profile of trimethyl borate fuel plus 1.5 percent potassium hydroxide additive. Run 12.

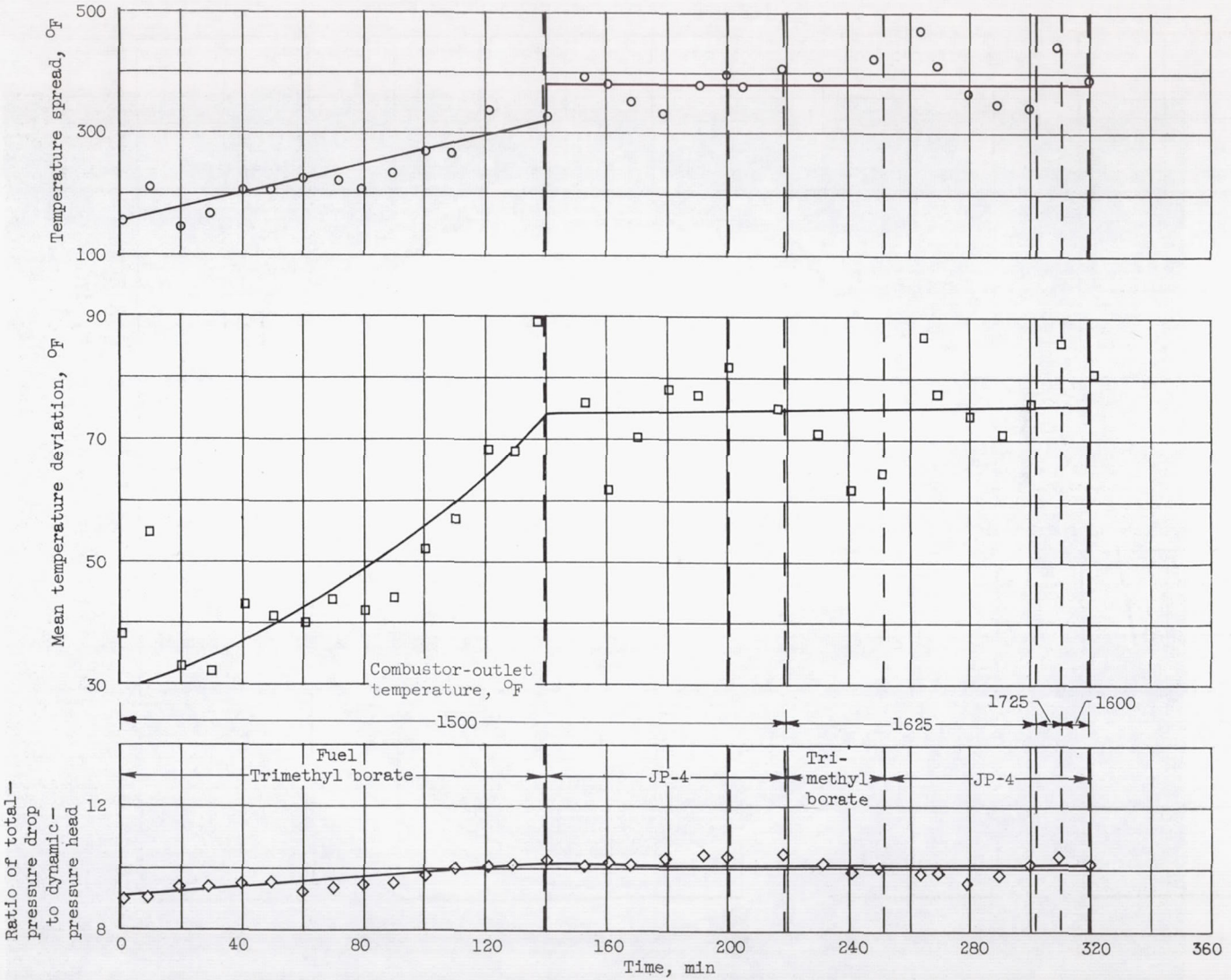


Figure 26. - Effectiveness of burning JP-4 fuel to remove deposits from liner walls. Run 27.

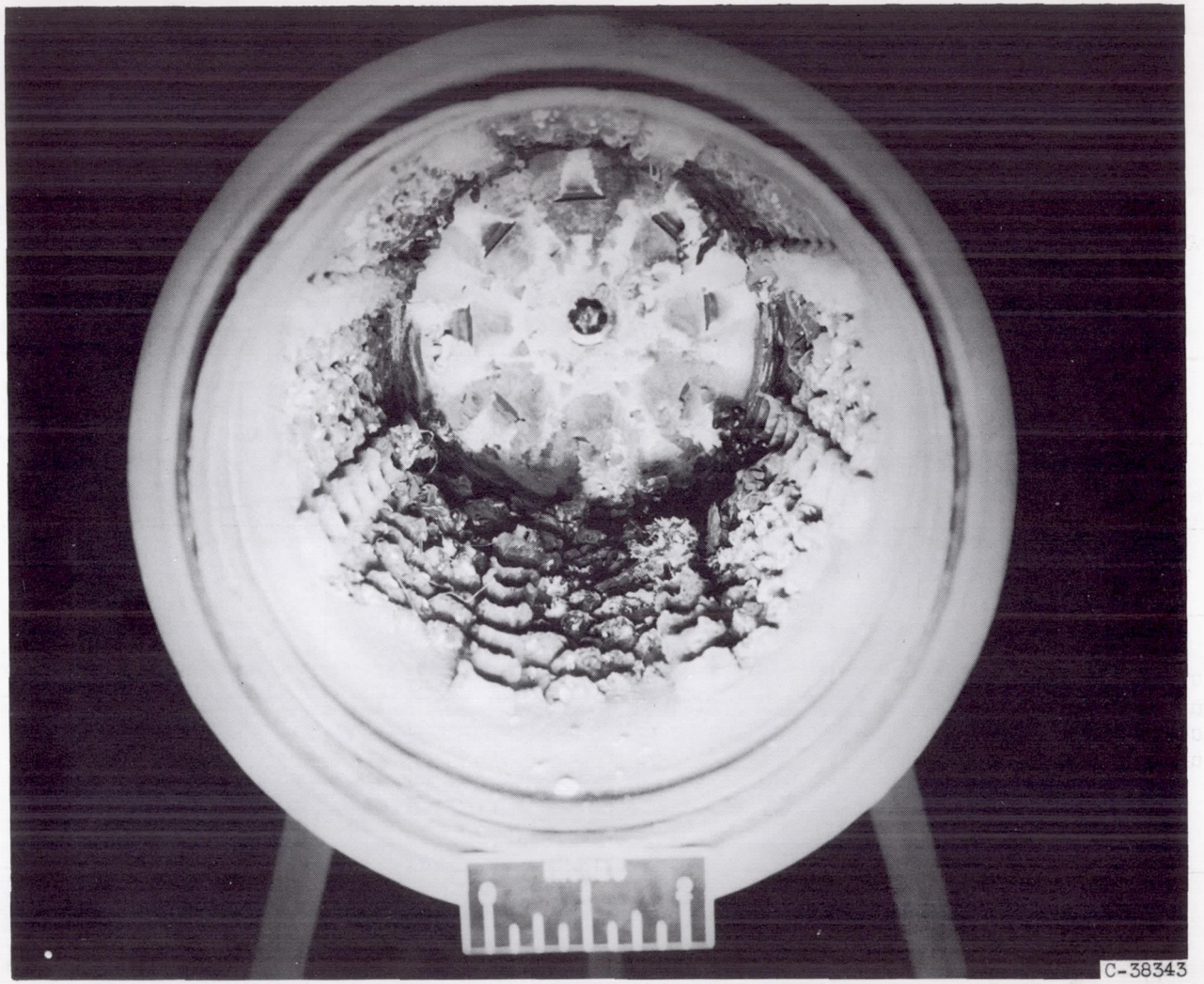
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(a) After 140 minutes of burning trimethyl borate, and 60 minutes of burning JP-4.

Figure 27. - Liner deposits. Run 27.

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(b) After completion of cleanout tests.

Figure 27. - Concluded. Liner deposits. Run 27.

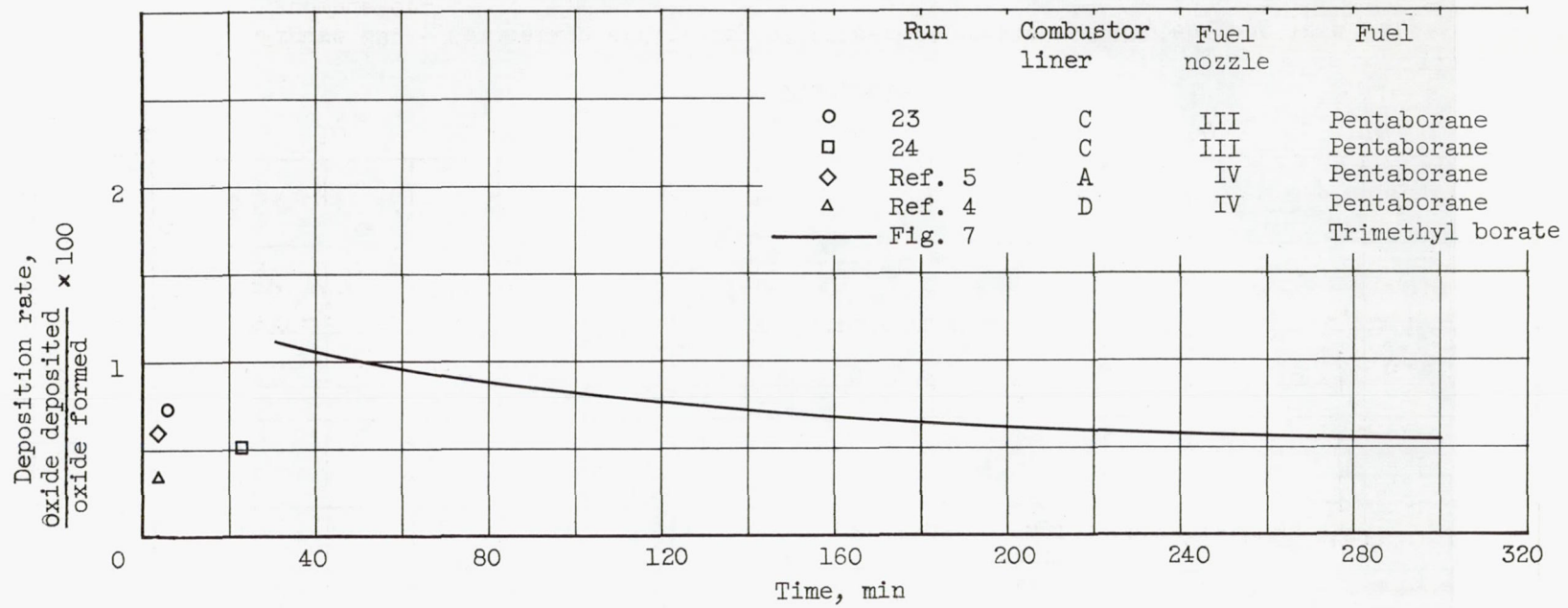


Figure 28. - Comparison of deposition rates obtained with pentaborane fuel and trimethyl borate fuel.

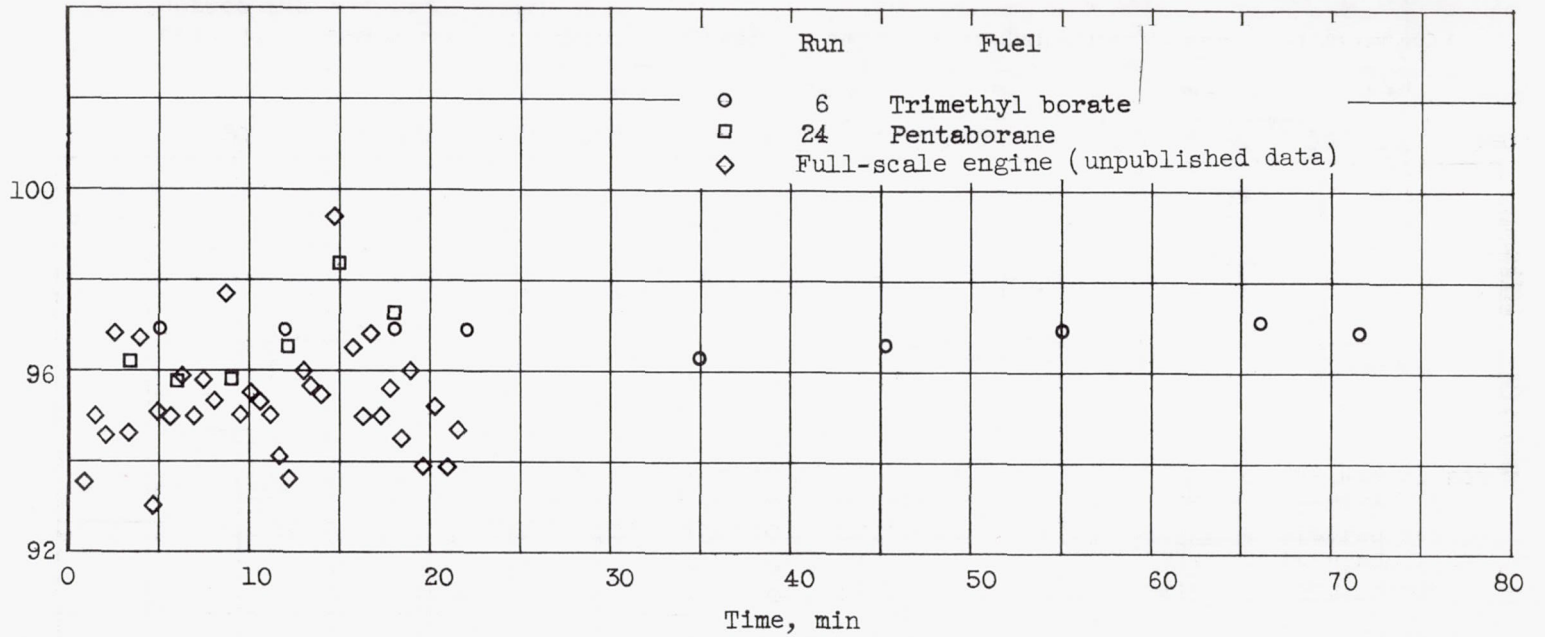


Figure 29. - Combustion efficiency of trimethyl borate and pentaborane in a J47 combustor.

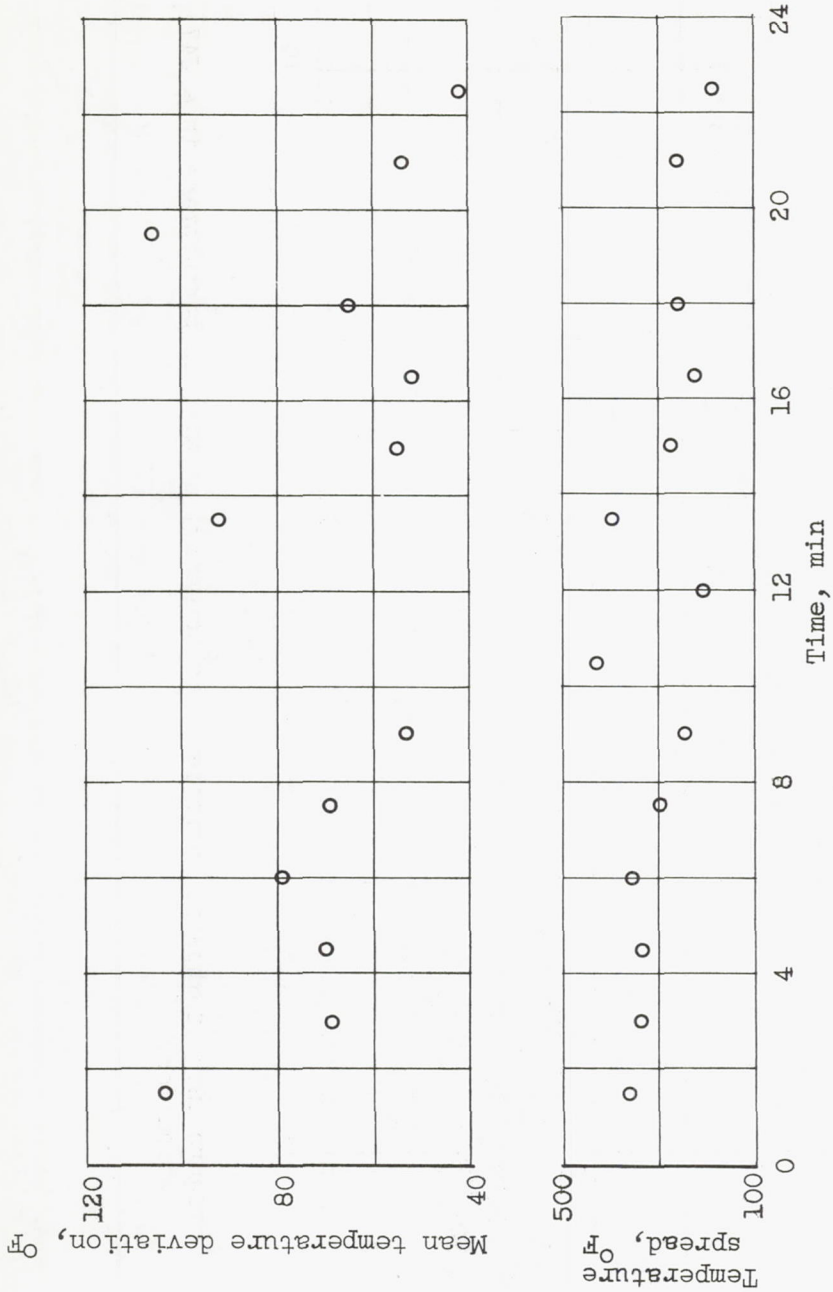
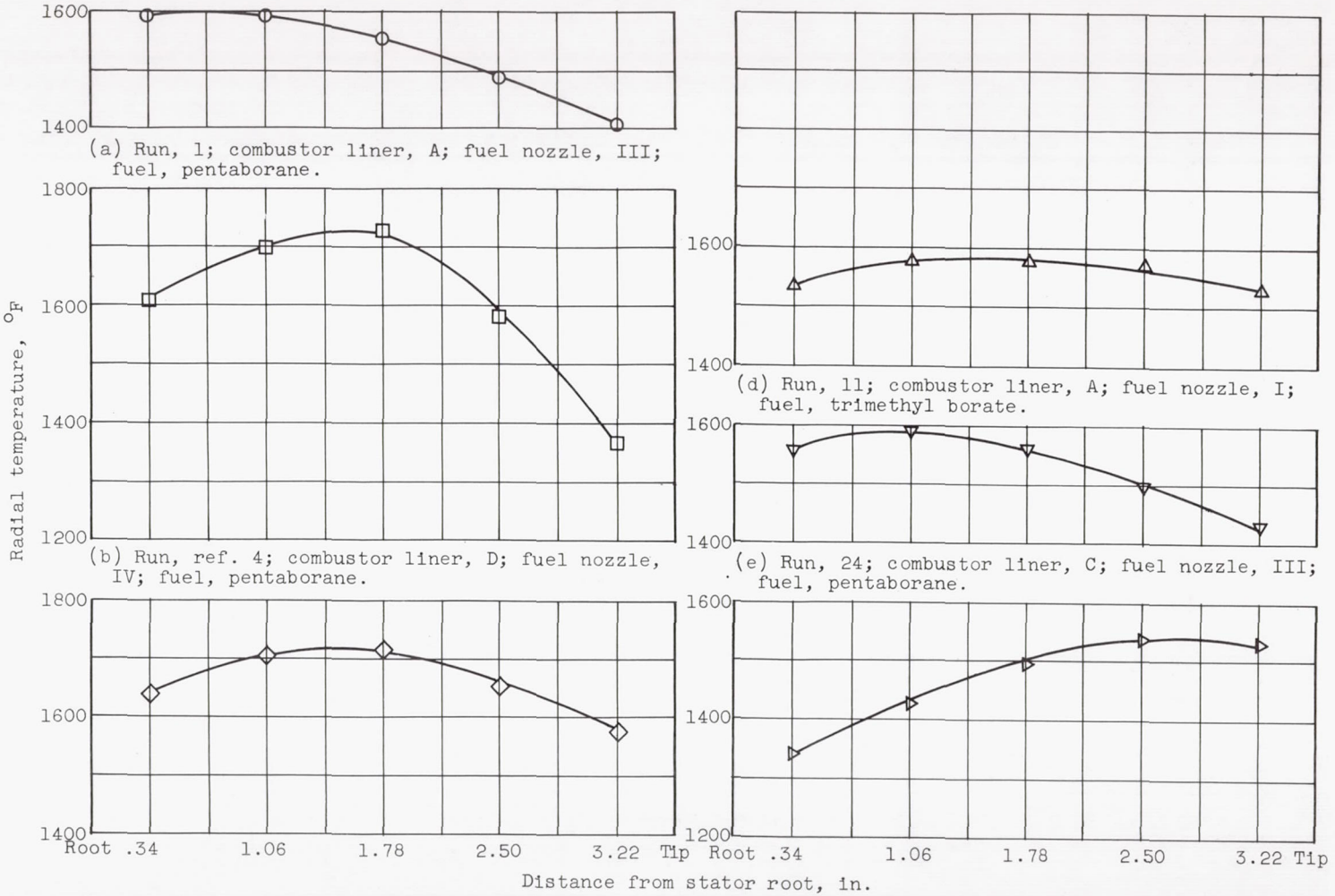


Figure 30. - Temperature spread and mean temperature deviation obtained with pentaborane fuel. Liner C; fuel nozzle III; run 24.



(a) Run, 1; combustor liner, A; fuel nozzle, III; fuel, pentaborane.

(b) Run, ref. 4; combustor liner, D; fuel nozzle, IV; fuel, pentaborane.

(c) Run, ref. 5; combustor liner, A; fuel nozzle, IV; fuel, pentaborane - JP-4 blend.

(d) Run, 11; combustor liner, A; fuel nozzle, I; fuel, trimethyl borate.

(e) Run, 24; combustor liner, C; fuel nozzle, III; fuel, pentaborane.

(f) Run, 24; combustor liner, C; fuel nozzle, III; fuel, JP-4.

Figure 31. - Combustor-outlet radial-temperature profiles obtained with several fuels.